Energy policy adjustments for building renovation in growing and shrinking cities

Energiepolitikanpassungen für Gebäudesanierung in wachsenden und schrumpfenden Städten
Zur Erlangung des akademischen Grades Doktor-Ingenieur (Dr.-Ing.)
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1. Gutachten: Prof. Dr.-Ing. Hans Joachim Linke
2. Gutachten: Prof. Harald Garrecht
3. Gutachten: Dr. Clemens Rohde

TECHNISCHE UNIVERSITÄT DARMSTADT

Institut für Geodäsie
Fachgebiet Landmanagement

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1 Acknowledgement

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Abstract

To mitigate climate change, buildings need to cut down on energy consumption drastically. The necessary technologies exist, and energy policy seeks to encourage building owners to implement appropriate measures. However, the policy instruments and their current designs fail to put buildings on a climate saving track. In recognition of the tremendous barriers, as the long cycles for retrofit and the substantial investments, this dissertation elicits the possibility to attach measures to a given megatrend: the growth of cities. What are the factors that influence the energy demand aside from the sheer growth? Is it possible to employ them to achieve more efficient investments and higher energy savings? This dissertation delivers the amplitude of migration's influence on energy demand and why it is not proportional to population growth. It further reveals the migration-related factors that drive energy demand and discusses them as triggers for potential policy adoption. The impact of such policy instruments is quantified and shows more energy can be saved at the same level of investment when considering migration processes.

Zusammenfassung

Um dem Klimawandel zu entschärfen muss der Energieverbrauch in Gebäuden drastisch gesenkt werden. Die dafür notwendigen Technologien sind verfügbar und es existieren energiepolitische Maßnahmen die Gebäudeeigner motivieren sollen sie umzusetzen. Entgegen wirken enorme Barrieren, wie beispielswiese die langen Renovierungszyklen und das hohe Investiitionsvolumen. Mit den aktuell wirkenden politischen Instrumenten und ihrer Ausgestaltung gelingt es deshalb bisher jedoch nicht die Gebäude auf einen Klimaschutzpfad zu bringen. Diese Arbeit eruiert die Möglichkeit politische Maßnahmen unter Nutzung eines Megatrends zu gestalten, nämlich des Wachstums von Städten. Welche Faktoren beeinflussen den Energiebedarf neben dem bloßen Wachstum? Ist es möglich diese Faktoren zu steuern um effizientere Investitionen und größere Energieeinsparungen hervorzubringen? Diese Dissertation liefert eine theoretische Quantifizierung der Größenordnung des Einflusses von Bevölkerungswachstum und -rückgang auf den Energiebedarf. Sie erklärt warum hier kein proportionaler Zusammenhang besteht und deckt Faktoren auf, die aus der Bevölkerungsbewegung entstehen und Energiebedarf antreiben. Diese Faktoren werden anschließend als Energieeinsparhebel für den Einsatz in politischen Maßnahmen diskutiert. Der Einfluss solcher politischen Maßnahmen wird quantifiziert und zeigt, dass bei gleichem Investitionslevel mehr Energie eingespart werden kann, wenn Bevölkerungswachstum und -rückgang in Städten berücksichtigt werden.

Contents

The atmosphere of our planet serves as a sink for everybody's greenhouse gases for no fee. Therefore, a clean and sustainable atmosphere follows the tragedy of common goods receiving only step-motherly care in a world that is dominated by market economies. The delayed price for the greenhouse gas absorption service is a change in climate that affects nearly everybody, some sooner and stronger but it reaches everywhere, in the end.

With the recognition of climate change and its gradual acceptance as an outcome of man-made greenhouse gas emissions the efforts towards the protection of our planet's climate have increased. After decades of negotiations, international, European and national policies have bit-by-bit taken up climate protection and the reduction of greenhouse gas emissions.[1] Scientific studies have facilitated the allocation of these emissions and confirm that the vast majority originates in energy consumption[2].

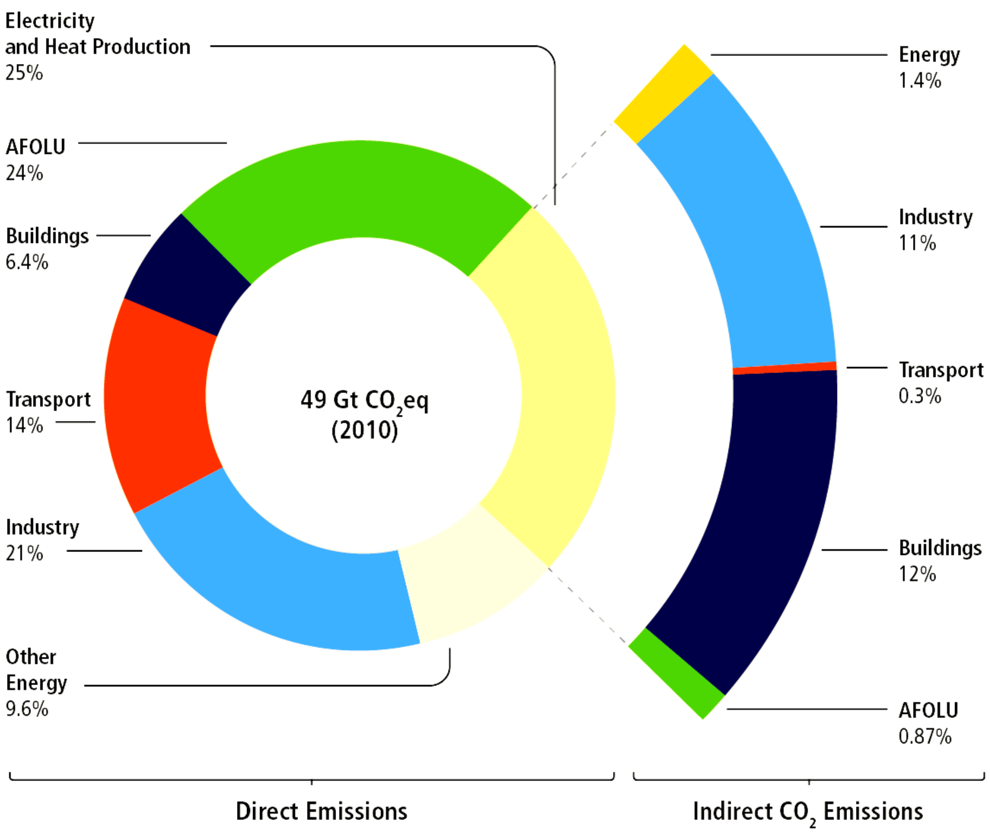


Figure 1: Global greenhouse gas emissions by economic sector: 18.4% caused by buildings (dark blue), directly and indirectly; source: IPCC et al., 2014

On average, buildings cause about 18.4% of greenhouse gas emissions worldwide, as shown in figure 1.[3] The largest energy consuming countries - developed countries, e.g. in Europe - spend about 40% of their energy within buildings causing almost 30% of greenhouse gas emissions. Space heating and warm water

[1] The timeline of climate policies is described in section 2.1.
[2] Studies on energy projection and scientific approaches are discussed in section 2.2.
[3] Figure 1 includesAgriculture, forestry and other land use (AFOLU).

in buildings cause 79% of the households' energy demand.[4] At the same time, buildings offer one of the largest energy saving potentials, most of which is accessible via mature technologies.[5]
Despite the availability of these technologies, this energy saving potential is locked up by massive barriers - why else would it still be existent? Therefore, strong effort is needed to access and exploit the buildings' vast energy savings potential. This ambition level is necessary to provide a sufficient contribution to greenhouse gas emissions reduction and limit the effect on our climate.[6]

For this reason, policy makers have been setting up a variety of instruments such as minimal energy performance standards, market based incentives, and numerous pilot projects and subsidy programmes to foster ambitious energy saving and efficiency measures within buildings. However, studies show that the climate goals cannot be achieved with the measures currently in place (Neuhoff et al., 2011, p. 11).

In parallel to the huge effort currently undertaken to shape up the existing buildings into sustainable ones, the building stock undergoes changes that are induced by demographic factors. Urbanization, the growth of cities, is an ongoing process that triggers new construction and shapes the way space is used. On the other hand, viable and conceivably efficient buildings are abandoned in shrinking cities. Both, growth and shrinkage potentially affect energy saving efforts. In shrinking cities, buildings may be renovated today and become vacant in the future. In the worst case, such unnecessary renovations are incited by policy instrument such as subsidies. In growing cities, energy demand may simply increase as more buildings are erected for the growing population.

The question this research seeks to answer is: How much does population growth or shrinkage in a city affect energy savings in buildings? How can policy be adjusted for demographic change? And if policy steered the energy investments well, could these achieve larger savings more efficiently?

To answer these questions the energy development of the buildings within big German cities is projected under the influence of population change factors. For this assessment, the first of three steps isolates the effect of population change from the effects of different building stocks whilst clustering the analysed cities as per building stock composition.[7] Secondly, three policy pathways are developed to explore the different energy saving targets.[8] Thirdly, the population-related drivers of energy savings are identified.[9] These three preparatory steps build the basis for the quantification of the effect a growing or shrinking population has on energy savings in buildings[10]. The results feed into the design of policy adjustments aiming to effectively use and incorporate these population growth effects in energy policy.

The analysis is applied to big German cities. At the time Germany was selected, it contained both growing and shrinking cities offering the same framework conditions to assess either growth development. However, since 2015 there are no more shrinking big cities in Germany due to the refugee crisis and urbanisation, as the regional statistics show (Regionalstatistik, 2017).

As the assessment explores the growth-related energy effects on existing cities, its results are applicable in reality. Additionally, the results will provide more insight on the differences amongst existing growing and shrinking cities which vary in their building stock composition. These differences provide a basis to determine suitable energy saving targets and adjust policies and renovation activity.

[4] https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings
[5] See section 2.2.
[6] See section 6.1.
[7] See chapter 3.
[8] See chapter 4.
[9] See chapter 5.
[10] See chapter 6.1.

The protection of earth's climate is solidly embodied in international, European and national politics. On the basis of the United Nations Framework Conventions on Climate Change (UNFCCC)[11] a large number of countries committed themselves to binding greenhouse gas emission targets in the Kyoto Protocol[12]. The Doha Amendmend to the Kyoto Protocol[13] It includes a second commitment period from 2012 to 2020. As the latest achievements, the Paris Agreement was reached at COP21[14] in Paris. It engages its parties to nationally determine voluntary contributions to fight climate change mitigation starting in 2021. It was ratified by 132 countries by December 2016.

As a contribution to the Paris Agreement, Europe has committed itself to a binding target of 40% reduction of greenhouse gas (GHG) by 2030 compared to 1990. This target is included within the EU intended nationally determined contribution (EU, 2016) on the basis of the 2030 climate and energy framework (EU, 2014). It succeeds the target from 2009, when the European Union had agreed to a 20% GHG reduction until 2020 within the decision of the European parliament (EC and Council, 2009).

Germany, as one of the biggest European energy consumers, has ratified the Paris Agreement in September 2016. Within the EU, Germany has committed to a greenhouse gas emission reduction of 14% in 2020 compared to 2005 (EC and Council, 2009). Member state contributions extending beyond 2020, for the period until 2030 are currently being drafted, in which Germany currently has a 38% greenhouse gas reduction target for 2030 compared to 2005.[15]

Essentially, the conservation of energy in buildings especially from fossil sources contributes largely to these goals. The EU has established energy related guidelines in addition to the emission trading scheme to achieve the reduction targets, in recognition of the large amount of greenhouse gas emitted for energy uses. Buildings represent one focus within the EU effort towards climate protection as they currently contribute by 36% to the CO_2 emissions in the EU by consuming 40% of the final energy (EU, 2017b). They are included multiple directives as the EPBD and the EED.

Most importantly for buildings, the Energy Performance in Buildings Directive (EPBD) includes a bundle of actions at national level. It requires minimum standards for new buildings and major renovations of existing buildings as well as retrofit of building parts. In addition, by 2020 all new buildings must be constructed according to nationally determined nearly zero energy. New governmental buildings are required to comply even by 2019. Therefore, the Member States need to individually define what a nearly zero energy buildings is. The directive also demands energy performance certificates in all advertisements for the sale or rental of buildings. Finally, countries shall list financial measures to ensure the energetic improvement of the building stock. The Energy Efficiency Directive (EED) demands member states to

[11] This framework facilitates international climate agreements on greenhouse gas emissions and came into force in 1994, see glossary UNFCCC.

[12] The Kyoto Protocol was adopted in 1997 and entered into force in 2005. The commitment period from 2008 to 2012 was ratified by 192 countries, including Germany, which reached its reduction targets, see BMUB, 2015.

[13] The Doha Amendment was ratified by 75 countries as of December 2016. Germany has not ratified.

[14] 21st session of the Conference of the Parties to the 1992 United Nations Framework Conventions on Climate Change or the United Nations Climate Change Conference 2015

[15] The Effort Sharing Regulation for 2021-2030 currently discussed was proposed in July 2016, see https://ec.europa.eu/clima/policies/effort/proposal_en.

establish national plans for renovating the overall building stock as part of the National Energy Efficiency Action Plans (EU, 2017a).

Parallel to the international activities, the targets for greenhouse gas emissions and energy savings in buildings have been evolving over time. Within the Integrated Energy and Climate Program[16] (IEKP) in 2007 Germany set itself targets for 2020, i.e. 40% GHG emission reduction compared to 1990 and 14% renewable energy for heating in buildings as well as an increase of minimum energy performance standards by 30%.[17] The German government issued an energy concept in 2010 which formulated two efficiency goals for the building sector. Until 2020, heat demand is to decline by 20%; and until 2050, primary energy demand in buildings shall be reduced by 80%. To support these goals an increase of the renovation rate from 1% to 2% was foreseen.

Measures to achieve these national and the contribution to European goals are listed within the German national energy efficiency action plan (NEEAP) of 2014, which includes a renovation strategy to additionally comply with the EED. In the same year, the government published the national action plan for energy[18] (NAPE) efficiency, which includes a continuation of subsidy programs. Only one year later, in 2015, subsidies are again refined to aim for more ambitious renovations and new buildings within the renovation plans included in the Energy efficiency Strategy in buildings. In 2016, the targets were sharpened on sector level within the climate protection plan[19] in connection to the Paris Agreement. Therein, Germany commits to a reduction of CO_2 emissions of 67-66% of final energy in buildings until 2030.

In the same year a greenbook process for energy efficiency[20] was initiated by the BMWi[21], which does not include a section on buildings. In spring 2017, the energy law for buildings was supposed to be enacted and set the nearly zero energy level for public buildings. However, the draft that set this energy level to KfW 55 standard[22] has little chance of being enacted before the elections and might become less ambitious afterwards. Despite all initiatives, it is still open how renovation activity and ambition level will be improved enough to fulfil the goals. The progress report on energy transition[23] shows that energy efficiency even decreased, i.e. the energy demand in households increased more than the living space. Hence, further political measures are needed to trigger more and deeper renovation action.

16 Bundesregierung, 2007

17 These minimum standards were finally enacted with the EnEV2009, see chapter 4.1.3.

18 Bundesregierung, 2014

19 Bundesregierung, 2016b, p. 26

20 Bundesregierung, 2016b

21 Federal Ministry for Economic Affairs and Energy (German: Bundesministerium für Wirtschaft und Energie) (BMWi)

22 According to the currently valid Energy Saving Ordinance of 2014 KfW 55 realized with envelope efficiency converts to a final energy demand of 37 kWh/m^2 for example in multifamily houses, see Enseling (2014). As the source states, envelope efficiency may be substituted with renewable energy resulting in a much higher energy demand.

23 BMWi, 2015

National projections of possible energy pathways for buildings are the basis for this assessment. Various studies for political decision makers include such projections and trajectories to achieve climate protection goals, as for example the studies Modell Deutschland[24], Politikszenarien[25], Energiereferenzprognose[26] and Klimaschutzszenario 2050[27]. All of these studies generate building stock projections for climate protection and compare ambitious scenarios to a defined baseline, as laid out by Haller et al., 2015. However, the approaches to create these projections vary.

The approach used in the Modell Deutschland is to generate climate target driven scenarios. This normative approach makes the ambitious scenarios achieve defined goals and facilitates the quantification of the effort to achieve them.

Opposed to that, the Politikszenarien approach the projection from a set of policy measures and explore the resulting energy saving amount. For the baseline scenario in the study Politikszenarien from 2013 for example, these measures were agreed upon in a coordination process between three federal ministries[28]. The measures for the ambitious scenario are independent from such political administration consensus and thus do not express any intention of the parties named. Resulting from the measure-based approach, the scenarios aim to show how much energy and ultimately greenhouse gas emissions can be saved, if certain political measures, as for example the building code, are applied or enhanced. This approach presents the reader an exploratory path with a given set of assumed measures.

Both approaches include comprehensive and in-depth modelling to assess the impact of policy-triggered building measures on energy consumption and greenhouse gas emissions. For example, the bottom-up representation of buildings and their current energy consumption already includes significant uncertainties, as different users show significantly different heating behaviour varying by 50% around the mean consumption according to Loga et al., 2007, (p. 23). Similar modelling questions arise when energy scenarios are generated for a nationwide building stock and bring to mind that any model, by nature, leaves out aspects that are unknown, indescribable or can not sufficiently be supported by available data.

Building energy modelling has been advanced by specialized researchers keep refining and enhancing national building models [29] to achieve reliable and robust results. The INVERT/EE-Lab model has been developed for more than a decade now and Müller, 2015 has redesigned and rewritten it. He expanded its scope to endogenously assess the impact of resource availability, energy or CO_2 prices, climate change and energy policy. For example, the model can now reflect the impact of several political instruments, such as financing schemes with efficiency quotas and premiums. Steinbach, 2016 contributed to that same model and introduced a reflection of the investor structure and their investment decision process. The investment decision includes the choice between different heating systems as well as between different envelope insulation levels. Bettgenhäuser, 2013 has developed $BEAM^2$ which also covers embodied energy

[24] Prognos AG and Öko-Institut e.V. (2009)
[25] Döring et al. (2013)
[26] Schlesinger et al., 2014
[27] Repenning et al. (2014)
[28] the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (German: Bundesministerium für Umwelt, Naturschutz, Bau und nukleare Sicherheit BMUB), the Federal Ministry of Finance (German: Bundesfinanzministerium BMF)and the Federal Environment Agency (German: Umweltbundesamt UBA)
[29] Bettgenhäuser, 2013 gives an overview of building models

in addition to the common technical and economical analysis. The information on embodied or grey energy, which is closely linked to life cycle analysis and circular economy considerations.

To enable these models for scenario generation, data on technologies and innovation are necessary. These innovations include improvements to use environmental energies present at the building envelope. Garrecht and Pfeifer, 2016, for example, present an assessment of three different composite building envelope components that differ not only in the material used but also in the physical heat flow processes. First calculations show that due to the integration of a solar air collector combined with a no-fines lightweight concrete in one of the components this option offers a better energetic behaviour at the same heat transfer coefficient. Systemic, out of the box approaches like this one enlarge the range for energetic building performance and potentially close the gap of needed energy savings and renewable energy use to achieve a sustainable climate.

The requirements for a model to support this analysis include the possibility to model policy instruments and to extract results by building type and building age. Various models fulfil these conditions, INVERT/EE-Lab was selected as it considers the different owner groups.

This work is roughly divided into the main assessment thread shown on the left-hand side of figure 2 and two accompanying analyses for assessing sensitivities, on the right-hand side. The sensitivity analyses in chapters 3 and 4 contain in-depth analyses about the existing building stock and political framework. These frameworks explain the background and setting in which the main analysis is situated, hence, they are conducted upfront. Additionally, these two assessments provide input for the impact assessment in chapter 6.

Chapter 5 contains the main analysis of the correlation and causality relation between demographic change and energy demand drivers within buildings. Each of the in depth analyses in chapters two, three and four contains its own method, results, discussion and interpretation. These interpretations focus on the further use within the impact analysis in chapter 6. The final scenario analysis combines the results of the city clustering (chapter 3), the policy pathways (4) and the growth factor analysis into scenarios that are designed to quantify the impact of demographic change on energy savings.

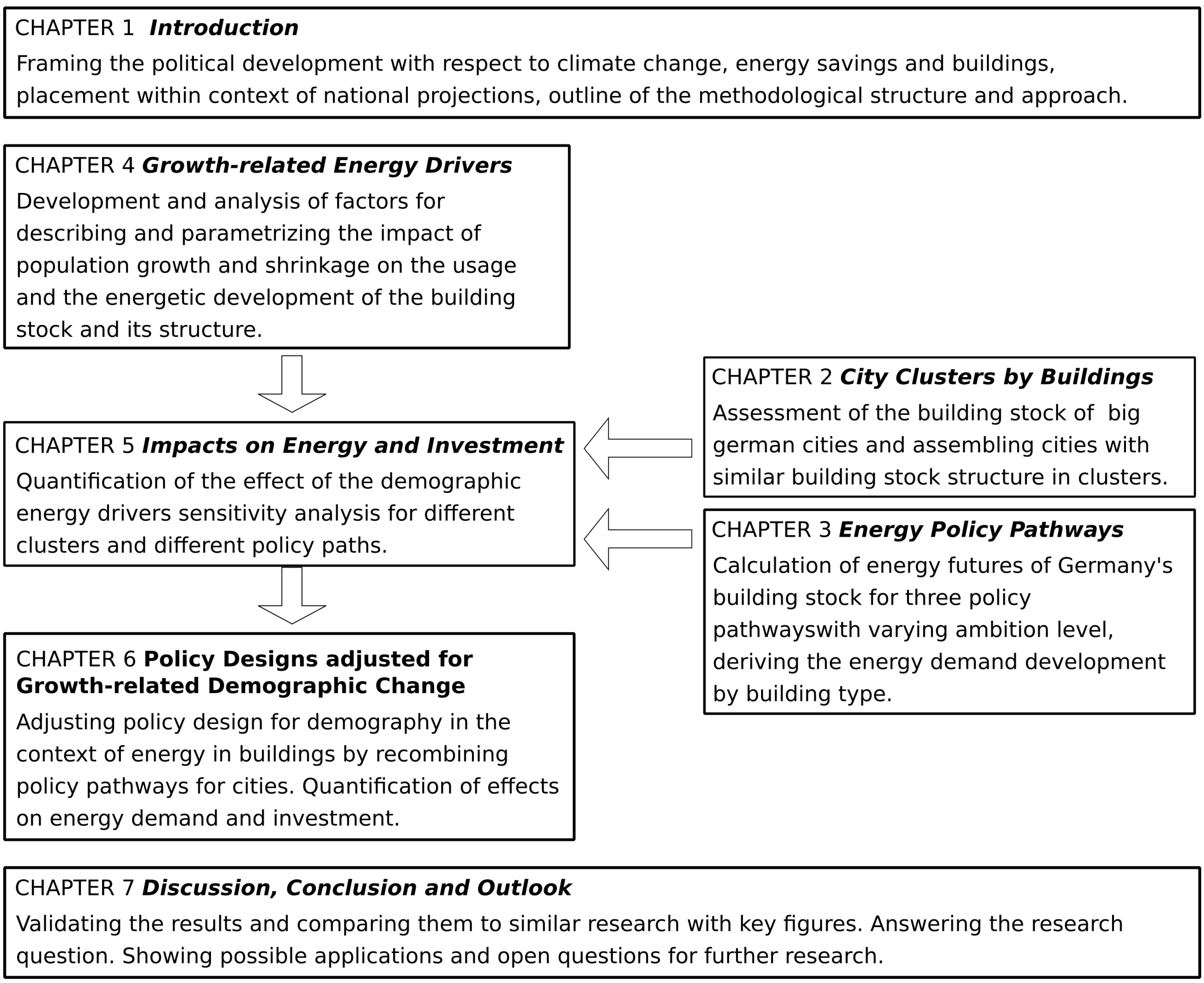


Figure 2: chapter structure

This research is structured into different analyses that each present a number of results, which are used in further assessments. To understand the nomenclature of the results, figure 3 provides a simplified overview of the designed pathways and scenarios and their recombination to answer the research questions. In chapter 5 growth-related energy drivers are assessed to distinguish three demographic developments. CONST assumes a constant population, GROW considers projected growth and shrinkage, GRIN additionally considers induced changes in living space per person. Chapter 4 covers the design of three national policy pathways for energy retrofit in buildings by ambition level, including a business as usual scenario BAU, a 80% and 95% greenhouse gas reduction scenario, CP80 and CP95 respectively. Chapter 6 combines these 6 results to assess the energy impact of demographic change. Thereby, the results are presented for different city clusters, which are determined in chapter 3 based on the cities' building stock structure. Finally, chapter 7 introduces policy designs that adopt the different demographic change within cities and combine policy measures accordingly. This chapter contains the answer to the question: Can demography-adjusted policy improve the efficiency of energetic retrofit investments in buildings?

2.4 Terminology

In this work, the terms growth, migration, demography and demographic change are used with a focus on the research question and thus to be understood as follows.

Growth and shrinkage of a city refer to the change in population count. The growth and shrinkage or positive and negative growth is henceforth subsumed in the term growth. For example, the impact of growth is meant to include the impact of the change in the population count in both, growing and shrinking cities. As the growth of a city may be affected by internal and external migration, both are meant when the term migration is used.

Within this work, the term demography is closely linked to migration. Demography or the science of the population assesses the development of population and its structure with respect to age, sex, size or geographical or societal distribution. Migration as one part of demography next to fertility, mortality, migration and population structure, is the predominant aspect for the assessments within the research at hand. (Müller, Nauck, and Diekmann, 2000)

Migration may change the population structure, for example when mostly young people move the average age of shrinking cities declines and the one of growing cities inclines. The implications of growth and certain growth-induced or migration-related demographic changes are thus included. Beyond the scope of this research are the analyse the age dependent heating behaviour or age-related investment behaviour in building energy measures.

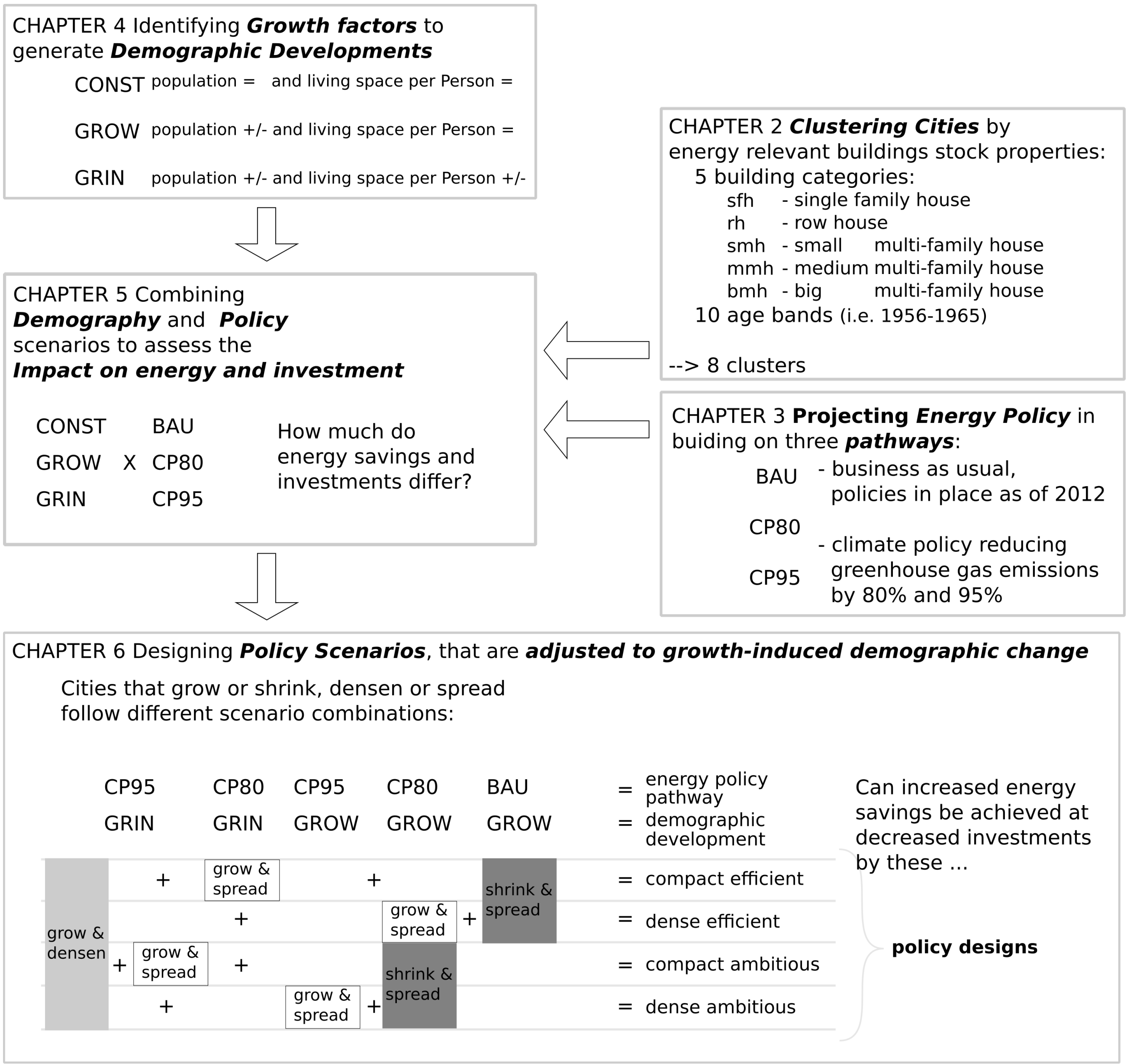


Figure 3: scenarios and their combination

3 City Clusters based on buildings

The city clustering provides insight on the cities building stock and serves as mean to exclude its influence. For this purpose comparisons are made between cities within one cluster and amongst the clusters within the growth's impact assessment in chapter 6.1.

3.1 Data preparation

The cluster analysis is based on multiple data sets of different structure that are combined to contain the relevant detail and enable the analysis on energy demand. After aligning the different aggregation levels of the building stock data, the number of buildings is converted into floor area to better reflect energy demand. The next step eliminates the city sizes by converting the absolute floor area for each building type into a relative share of the total floor area of each city.

Combining building stock and the energy data into one dataset involves the alignment of building sizes and building ages.The building stock data stem from the official census data collection of 2011, updated in May 2014 (Statistisches Bundesamt, 2014). They contain details on how many buildings of what kind exist in each of the assessed 76 German cities, which inhabit 100.000 inhabitant and more. For the purpose of this energetic analysis the data were queried by construction period, number of residential units, and attachment type[30]. These properties form a data set of 200 dimensions resulting from the combination of 10 building periods, 4 attachment types and 5 sizes in the structure that is illustrated in table 21.

Table 1 shows how the data sets are aggregated with respect to the construction period that indicates the building age. It also provides some historical background on the periods marking the World Wars I and II and the introduction of energy saving policies for buildings as milestones for the building stock structure.

Table 1: Aggregation of construction periods, historic interpretation from Effenberger, Banse, and Oertel, 2014

building period Census 2011	building period IWU 2010	building period in this analysis	Historic events with effect on building stock and construction
before 1919	before 1919	before 1919	World War I
1919 - 1948	1919 – 1948	1919 - 1948	World War II
1949 - 1978	1949 – 1957 1958 – 1968 1969 – 1978	1949 - 1978	Germany's separation: East: construction mainly big mfh, sfh[31] only 10% West: living space demand doubled[32]
1979 -1986	1979 – 1983	1979 - 1986	West: first ordinance on thermal insulation 1977
1987 - 1990 1991 - 1995	1984 - 1994	1987 - 1995	West: second ordinance on thermal insulation 1982
1996 - 2000 2001 - 2004 2005 - 2008 2009 and later	1995 – 2001 2002 - 2009 2010 - . . .	1996 - 2011	Third ordinance on thermal insulation 1995 Energy Savings Ordinance 2002 Energy Savings Ordinance 2009

The building structure of census data shown in table 2 is aligned with the data set on energy demand. The number of units and the attachment type are aggregated into building types. The combination of building type and building age then returns 50 building segments:

[30] attachment types are: detached, attached or row house, semi-detached, other house

$$\text{number of buildings}_{\text{c,bty,age}} = \text{number of buildings}_{\text{c, bseg}} \tag{1}$$

c	- city	btyp	- building type
age	- construction period	bseg	- building segment

Table 2: Aggregation of census data by number of units and attachment type to obtain building types

units	attachment	building type	building type description
1 and 2	attached	rh	row house
1 and 2	detached	sfh	single family and semi houses
	semi-detached	sfh	
	other	sfh	
3-6	all attachments	smh	small multifamily house
6-12	all attachments	mmh	medium multifamily house
13 and more	all attachments	gmh	grand multifamily house

The number of buildings is transformed into floor area. Instead of continuing with the number of buildings, the cluster analysis shall be based on the total floor area. The area reflects the energy demand more closely as buildings vary significantly in their size. To obtain the floor area for each building type in each city two factors are used. The first factor contains the specific floor area per building type (IWU, 2003, p. 4-9). As building sizes differ across cities a second city specific adjustment is needed. This second adjustment uses one factor for all buildings types to calibrate the total floor area of the city to the empirical base (IWU, 2003). Finally, the total floor area for each building type is available for all cities. As this is an average approximation across Germany, the correction factor accounts for city specific differences in building sizes and calibrates the resulting area to the total floor area of the city.

$$\text{Floor area}_{\text{bseg}} = \text{number of buildings}_{\text{c, bseg}} * \text{mean area per building}_{\text{bseg}} * \text{adjustment factor}_{\text{c}} \tag{2}$$

$$\text{A}_{\text{c,bseg}} = \text{n}_{\text{c,bseg}} * \text{a}_{\text{bseg}} * \text{adj}_{\text{c}} \tag{3}$$

Firstly, this relationship is expressed indifferent of the city size. Bigger cities may grow differently than a smaller city, they are both assumed to keep the building type composition.[33] To be able to compare cities of different sizes, the analysis is based on the percentage share of each building segment.

With the total floor area of a city being

$$T_c = \sum_{i=1}^{k} A_{\text{c, bseg}} \tag{4}$$

[33] New construction is assumed to keep the composition of the last building age, i.e. new building composition of 2011.

the share of each building segment is:

$$s_{\text{c, bseg}} = \frac{A_{\text{c, bseg}}}{T_c}. \tag{5}$$

T_c	- total floor area of a city
$s_{\text{c, bseg}}$	- share of T_c per building segment
$A_{\text{c, bseg}}$	- floor area per building segment
k	- number of building segments = 30
n	- number of cities = 76

Hence, for each city j there is a vector S_j containing the floor area shares s_i for all building types $i = [1, 2, \ldots, k = 50]$.

$$S_j = [s_1, s_2, \ldots, s_k] \tag{6}$$

These vectors for all cities form the data matrix A, which will be the basis of the further calculations.

$$A = \begin{bmatrix} S_1 \\ S_2 \\ \vdots \\ S_n \end{bmatrix} \tag{7}$$

Compositional data properties apply to the dataset. As the building stock now expressed as a shares of the city's total floor area, they form compositional data with specific properties. Compositions are portions of a total and thus always positive (Pawlowsky-Glahn and Egozcue, 2006, p. 3). Furthermore they are not independent, as they can not exceed 100%.

The compositional data need to be transformed in order to apply clustering algorithms. These algorithms require additivity and scalability. The behaviour of compositional data is not linear with respect to addition[34] and scalar multiplication as common in vector space. Therefore, the compositional observations need to be transformed. Boogaart and Tolosana-Delgado, 2013 suggest the transformation by applying a logarithmic function.

The next step, transforms the data from a constrained sample space into an unconstrained vector space. The compositional data analysis has been essentially developed by Aitchison, 1986, who proposes the additive-log-ratio (alr) and the centered-log-ratio (clr) to represent compositional data in real space. However, these log-ratios have drawbacks. The alr coordinates cannot be mapped onto orthogonal axes because the axes are actually at 60° and the clr-transformed observations lie on a plane in D-dimensional real space. Thus, the covariance and correlation matrices for clr-representations are singular, i.e. their determinant is zero.

$$\text{clr}(s_i) = \ln\left(\frac{s_1}{\sqrt[k]{\prod_{l=1}^{k} x_l}}\right) = \ln\left(\frac{s_1}{(x_1 \times x_2 \times \ldots \times x_k)^{1/k}}\right) \tag{8}$$

[34] For example, compositional data can only add up to a maximum of 1.

To avoid these drawbacks Egozcue et al., 2003 developed a third method, the isometric log-ratio (ilr) transformation. On the ilr representations, any classical multivariate data method can be performed for their analysis, as they are coordinates in an orthogonal system, a Euclidean space.

$$\mathrm{ilr}(s_i) = \sqrt{\frac{1}{i(i+1)}} \ln\left(\frac{\prod_{l=1}^{i} s_l}{(s_{i+1})^i}\right) = \sqrt{\frac{1}{i(i+1)}} \ln\left(\frac{s_1 \times s_2 \times \ldots \times s_i}{(s_{i+1})^i}\right) \tag{9}$$

Clustering allows to identify objects with similar properties. It is a statistical method that compares objects by these properties and bundles similar objects into clusters. For this analysis, clustering the cities facilitates the isolation of the growth effect on energy demand. In order to isolate the effect of growth on energy demand, other energy relevant factors need to be minimized. Besides the size of the city, the building stock composition of a city is relevant for its energy consumption. The composition is described by energy relevant properties[35] for real cities. To identify cities that carry comparable properties, all German cities more than 100.000 inhabitants are clustered with regard to this composition.

The curse of dimensions requires a clustering approach suitable for high dimensional data to cluster the numerous properties of the buildings stock data. This effect entails that objects with a clear clustering in few dimensions may not be as easily clustered in more dimensions. It occurs because the properties that identify the cluster become indistinct within the overall mass of properties, as their number increases. In other words, the reason for this behaviour is that each new dimension increases the space between all data points, but does not keep similar data points close in the same way. As a result, similarity measures like the Euclidean distance lose their expressiveness. Hence, clustering algorithms struggle to find the clusters on these data.

Reducing dimensions with principle component analysis (PCA) counteracts the loss of differences in high dimensional data. It increases the influence of the significant dimensions and reduces the number of dimensions by compressing the information and the variance into few orthogonal components. The resulting principle components are a mix of different building types with varying weight and thus not easily read or interpreted by themselves. However, they serve as a basis for the following clustering step (Backhaus, 2011).

The number of components are chosen based on the principle components based on the scree test. The scree plot shows that after a certain principle component the explanatory value, expressed as the eigenvalue of the component as a share of all eigenvalues, decreases rapidly. According to the scree test(Bacher, 1994, p. 309), the principal components before the rapid decline should be used for the following clustering step.

The clustering algorithm selected is the k-means approach. According to Bacher, Pöge, and Wenzig, 2010, p. 348 there is not only one correct choice of the clustering algorithm. He recommends the k-means approach for partitioning rather large populations. As the cities are clustered for the purpose of energetic comparison, there might be cases where one or more cities can be assigned to different clusters equally well. In that case the cities could be compared to either one of the clusters. However, for this analysis it is not necessary to find all similar cities. The goal is to find energetically similar cities that have a different growth rate, in order to separate the growth effect from the influence of different building stocks. The partitioning k-means algorithm suffices for this purpose. For further analysis of the clusters, however, it is necessary to know, that a quasi-hierarchichal clustering approach will find overlapping clusters on these data.

[35] described in section 3.1

The k-means approach is one of the most comprehensible clustering algorithms (Bacher, 1994, p. 309). K-means is an iterative algorithm and it starts by distributing the selected number of cluster centres randomly. In a second step, each data point is assigned to the closest centre. After that, the centres are updated and moved to the centroid position of the data points assigned to it. The centroid is the mean position of all the points in all of the coordinate directions. Subsequently, the assignment and updating of centroids is repeated until stability is achieved i.e. the cluster assignments of individual records are no longer changing. Apart from the number of clusters, the result is also dependent upon the chosen seed. The seed determines the location of the initial cluster centres. The results may vary with a different seed. To obtain a robust result the seed and number of clusters were varied. This algorithm was performed on the principle components, as it is not designed for high dimensional data.

Validation of the clusters is performed on the basis of historic city data . To verify, that these resulting clusters have explanatory value and fit into the historic background, the cities are compared using criteria apart from buildings stock data. These criteria are historic data with impact on the building stock, as for example the historic population development, which has impact on the weight of the building age classes. Other criteria are the number of students, the population density and the year when the 100.000 inhabitant mark was first reached. All three present evidence for the mix of the type and age of buildings[36]. These surrounding information help to interpret and validate the chosen clusters. Especially the periods in which population grows determine the share of these building types as these periods have their own characteristics with respect to architecture and city planning.

[36] Studentenzahlen: Statistisches Bundesamt (Destatis), 2017 | Stand: 03.05.2017 - 130731

3.3 The 8 City clusters

The k-means clustering was performed on three principle components according to the scree test, that chooses all components to the left of the first inflection point. Figure 4 shows a distinct inflection point behind the third component. Hence, the first three components are selected and cover 53.1% of the original information given in the building segments.

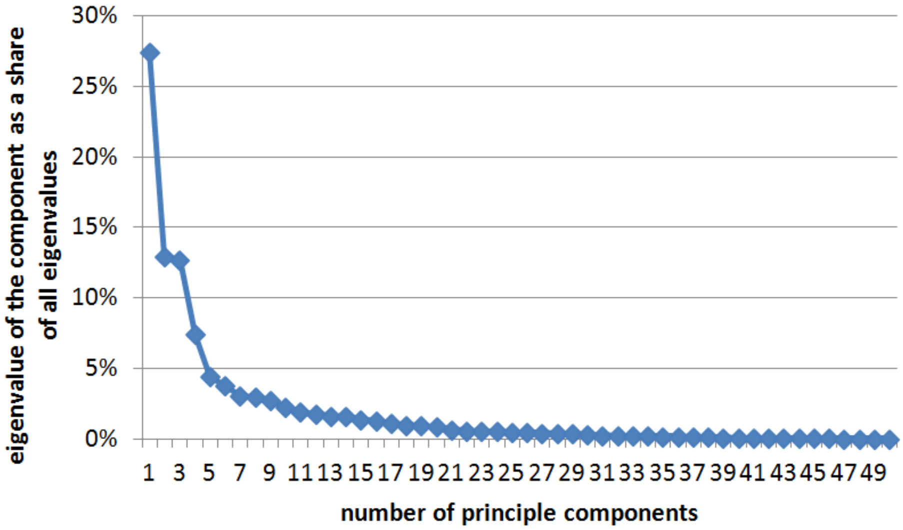


Figure 4: eigenvalue of the components principle components

The number of clusters were varied for selection. Comparing the results, it appears that structure of 8 clusters solves some of the clustering conflicts. For example, this structure recognizes the difference in clusters 7 and 8 found within the scheme of 5 clusters but ignored in that of 6 and 7 clusters. With higher number of clusters more and more exceptions occur. However, they can be used as an indicator to show which cities may not be as close to the other ones in the same cluster.
The geographic distribution of the cities does not identify all of the clusters. The cluster with "Former GDR" cities is the only one that may be distinctively identified by geographic location in the

Table 3: results of k-means clustering with a variation of the number of clusters k

id	city	clusters	$k = 5$	$k = 6$	$k = 7$	$k = 8$	$k = 10$	$k = 15$
4	Berlin	1	5	5	5	5	5	5
12	Chemnitz	1	5	5	5	5	5	13
15	Dresden	1	5	5	5	5	5	13
18	Erfurt	1	5	5	5	5	5	13
27	Halle (Saale)	1	5	5	5	5	5	13
35	Jena	1	5	5	5	5	5	13
42	Leipzig	1	5	5	5	5	5	13
46	Magdeburg	1	5	5	5	5	5	13
62	Potsdam	1	5	5	5	5	5	13
67	Rostock	1	5	5	5	5	5	13
8	Bottrop	2	4	4	4	4	9	9
3	Bergisch Gladbach	2	4	4	4	4	4	4
29	Hamm	2	4	4	4	4	9	9
43	Leverkusen	2	4	4	4	4	9	9
49	Moers	2	4	4	4	4	9	9
32	Heilbronn	3	1	6	1	1	1	8
60	Paderborn	3	1	6	1	1	6	6
58	Oldenburg (Oldenburg)	3	1	6	1	1	6	6
54	Neuss	3	1	6	1	1	1	1
66	Reutlingen	3	1	6	1	1	1	1
74	Wolfsburg	3	1	6	1	1	1	1
34	Ingolstadt	3	1	6	1	1	6	6
19	Erlangen	4	2	2	6	6	8	6
53	Münster	4	2	2	6	6	8	6
23	Fürth	4	2	2	6	6	8	14
5	Bielefeld	4	2	2	6	6	8	14
7	Bonn	4	2	2	6	6	8	8
72	Ulm	4	2	2	6	6	8	14
47	Mainz	4	3	2	6	6	2	14
76	Würzburg	4	3	2	6	6	3	14
31	Heidelberg	5	3	3	3	3	10	12
2	Augsburg	5	3	3	3	3	3	3
17	Düsseldorf	5	3	3	3	3	10	12
21	Frankfurt am Main	5	3	3	3	3	10	12
28	Hamburg	5	3	3	3	3	3	3
30	Hannover	5	3	3	3	3	3	3
36	Karlsruhe	5	3	3	3	3	10	12
38	Kiel	5	3	3	3	3	10	12
40	Köln	5	3	3	3	3	10	12
48	Mannheim	5	3	3	3	3	10	12
52	München	5	3	3	3	3	3	3
55	Nürnberg	5	3	3	3	3	3	12
57	Offenbach am Main	5	3	3	3	3	10	12
64	Regensburg	5	3	3	3	3	3	3
70	Stuttgart	5	3	3	3	3	10	12
22	Freiburg im Breisgau	5	3	3	3	3	3	14
71	Trier	6	2	2	2	2	2	15
13	Darmstadt	6	2	2	2	2	2	2
45	Ludwigshafen am Rhein	6	2	2	2	2	2	15
1	Aachen	6	2	2	2	2	2	2
25	Göttingen	6	2	2	2	2	2	2
44	Lübeck	6	2	2	2	2	2	10
75	Wuppertal	6	2	2	2	2	2	2
9	Braunschweig	6	2	2	2	2	2	10
37	Kassel	6	2	2	2	2	2	2
14	Dortmund	6	2	2	2	2	2	15
26	Hagen	6	2	2	2	2	2	15
73	Wiesbaden	6	3	2	2	2	10	2
11	Bremerhaven	6	3	3	2	2	10	10
59	Osnabrück	7	1	1	7	7	1	11
61	Pforzheim	7	1	1	7	7	8	8
41	Krefeld	7	1	1	7	7	7	11
51	Mülheim an der Ruhr	7	1	1	7	7	7	11
65	Remscheid	7	1	1	7	7	7	11
56	Oberhausen	7	1	1	7	7	1	11
69	Solingen	7	1	1	7	7	1	11
50	Mönchengladbach	7	1	1	7	7	1	11
63	Recklinghausen	7	1	1	7	7	1	11
39	Koblenz	8	2	1	7	8	7	8
6	Bochum	8	2	1	7	8	7	7
16	Duisburg	8	2	1	7	8	7	7
33	Herne	8	2	1	7	8	7	7
10	Bremen	8	2	1	7	8	7	11
20	Essen	8	2	1	2	8	7	7
24	Gelsenkirchen	8	2	1	2	8	7	7
68	Saarbrücken	8	2	1	2	8	7	7

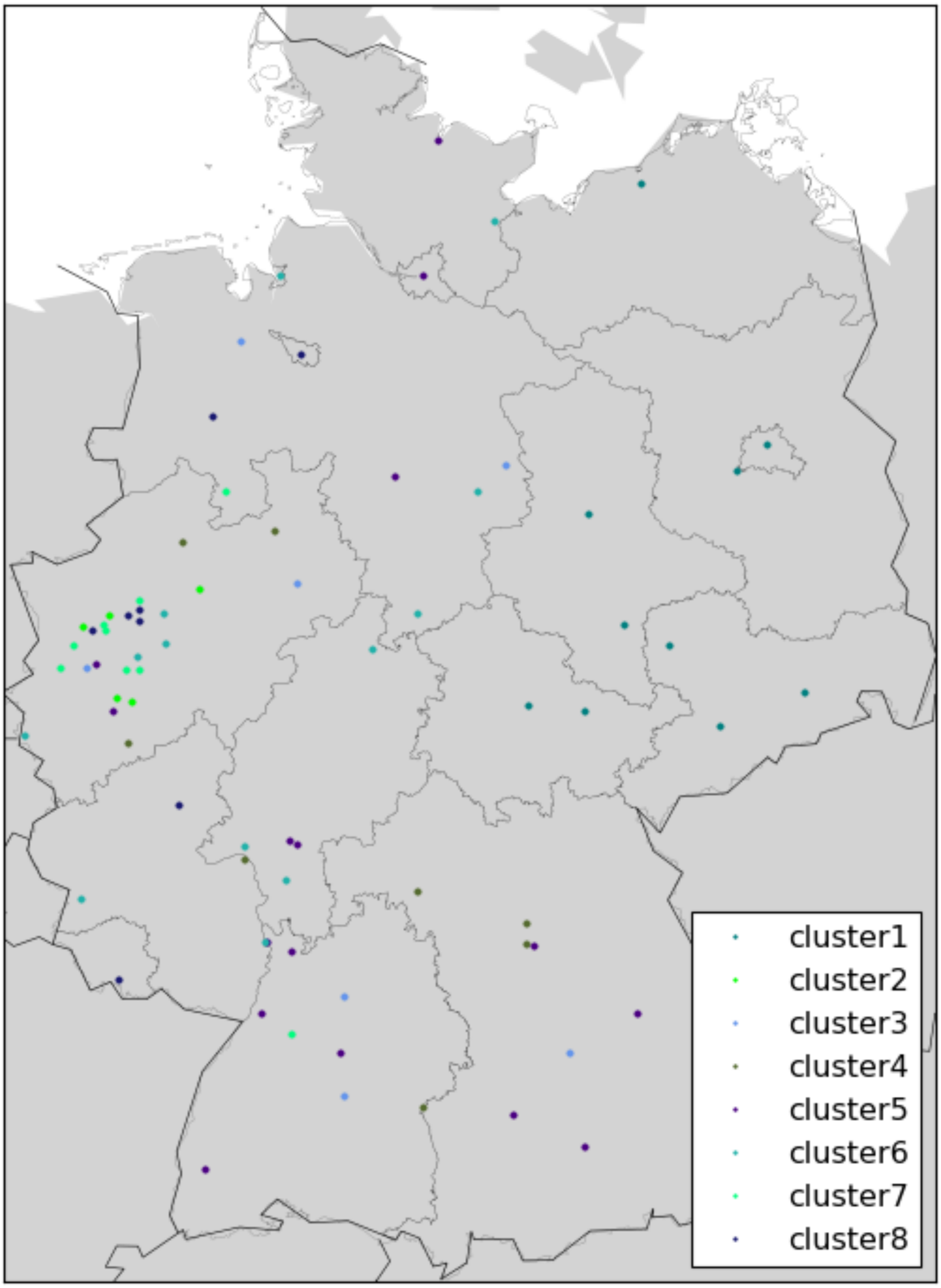


Figure 5: geographic distribution of the cities and their cluster

Finally the clusters are validated, using the city data in table 4 that may explain the development of the building stock and thus for example its age structure. The validation data include the historic population change, the number of students and the year when the 100.000 inhabitant mark was first reached. The next table shows how the clusters differ through the average values of these city properties.

Table 4: historic cluster properties, source: data from Destatis, 2011

cluster	population change in% 1940 -1960	1960 -1970	1970 -1990	1990 -2011	100k since	share of students 2011	people per km^2 2011	people 2011	size
1	0.99	1.04	1.09	0.93	1888	0.08	1459	572,155	giant
2	1.55	1.14	1.75	1.00	1969	0.00	1362	133,156	footnotesize
3	1.53	1.25	1.35	1.07	1972	0.04	1117	132,245	footnotesize
4	1.36	1.19	1.23	1.06	1940	0.18	1510	199,008	medium
5	1.24	1.03	1.00	1.04	1891	0.08	2320	541,120	giant
6	1.25	1.06	1.01	0.97	1918	0.10	1415	222,480	medium
7	1.28	1.03	1.09	0.94	1928	0.04	1675	167,149	footnotesize
8	1.20	0.98	1.14	0.92	1911	0.08	2063	332,166	large

Germany's history left its traces in the building stocks. The differences between the building stocks of cities in Western Germany and cities in the former GDR[37] results from the different urban planning and construction. More than in the western part it was common in eastern Germany to build prefabricated large-panel system buildings (German: Plattenbau), in residential block districts to fulfil the demand for living space in the late 70s and 80s. This historic development has a dominant effect and clearly distinguishes the eastern cities from the western ones within the cluster analysis. According to Hence, the first cluster FORMER GDR contains only eastern German cities, which on average have a tendency to shrink slightly between 1940 and 1960, while the population of all other cities grows, see table 4.As opposed to that, clusters 2 and 3 grow strongly within that time period and clearly distinguish from the other western German clusters 4 through 8, which grow moderately.

Clusters 2 and 3 begin to separate within the next two periods between 1960 and 1970 as well as 1970 and 1990. While in cluster 2 the growth is first slowing down to come back even stronger, cluster 3 follows a more balanced growth. On average, cities in both clusters reach the 100.000 inhabitant mark around 1970 which is significantly later than all other clusters, accordingly they will be called TEENS. In addition, the average city sizes in 2011 are very similar at a level of 130.000 inhabitants,compare table 4. Distinguishing between these two clusters are the share of students which is 10 times higher in the 3rd cluster and the population density which is about 20% higher in the 2nd cluster. A geographic analysis shows that the latter is entirely situated in the Ruhr area while cluster 2 is spread across different federal states. Due to these characteristics the names RUHR TEENS and COMMON TEENS are used for these clusters.

Cluster 4 can be easily separated from others, as it has the highest share of students with 18% on average, hence it will be called ACADEMICS. However, there are cities within that clusters with few students, as Fürth, which does not have an university, academy or college. Hence, other distinguishing elements are the moderate constant growth and the medium size.

[37] German Democratic Republic

A high density can also be found in cluster 5, however, this cluster contains very big cities, its average size is 540k inhabitants in 2011 and rising. These AGED GIANTS have mostly been important for a long time and thus reached the 100k marker early, and have a high density.

The differences between clusters 6 and 7 may not appear large, however the city size in cluster 6 is 33% higher whereas the density is 20% higher in cluster 7. Cluster 6 cities are spread across many federal states and have a 3% shrinking rate between 1909 and 2011. Related to their spread, their medium size and growth, and their skimmed population they are called SKIMMMED COMMONS.

All but two cities of cluster 7 are located within the Ruhr area.Hohn (1991) shows that these two cities were heavily destroyed during the air strikes in the World War II. Subsequently, the need for rapid construction and a lack of building material characterizes the architecture of these cities. As they are comparably footnotesize and their population is slowly shrinking cluster 7 cities shall be called SHRINKING DWARFS.

On average, cities in cluster 8 shrink in the 1960s and grow moderately between 1970 and 1990. They are old large cities, i.e. such that have been large before 1933 with the exception of Koblenz. Most of the cities are in the Ruhr area. The three remaining cities, Bremen, Koblenz und Saarbrücken were largely destroyed during air bombing in the second world war, as documented by Hohn (1991). All of them needed an essential amount of construction in a time with few resources to share across Germany. In addition to these historic characteristics, the mean population density in this cluster is the second highest, which distinguishes these cities from cities in cluster 7. As a result, the cities of cluster 8 are called SHRINKING MINES. The city clusters are fully listed in table 5.

Table 5: clusters

Cluster 1 FORMER GDR	Cluster 2 RUHR TEENS	Cluster 3 COMMON TEENS	Cluster 4 ACADEMICS	Cluster 5 AGED GIANTS	Cluster 6 SKIMMED COMMONS	Cluster 7 SHRINKING DWARFS	Cluster 8 SHRINKING Mines
Berlin	Bergisch Gladbach	Ingolstadt	Erlangen	Heidelberg	Ludwigshafen a. R.	Osnabrück	Essen
Chemnitz	Hamm	Paderborn	Bielefeld	Freiburg i. B.	Wiesbaden	Solingen	Gelsenkirchen
Dresden	Moers	Oldenburg	Würzburg	Regensburg	Braunschweig	Remscheid	Duisburg
Erfurt	Bottrop	Reutlingen	Mainz	Stuttgart	Bremerhaven	Pforzheim	Herne
Halle (Saale)	Leverkusen	Heilbronn	Ulm	Köln	Lübeck	Mönchengladbach	Bremen
Jena		Wolfsburg	Münster	Mannheim	Hagen	Krefeld	Bochum
Leipzig		Neuss	Fürth	Nürnberg	Darmstadt	Oberhausen	Koblenz
Magdeburg			Bonn	Frankfurt a. M.	Göttingen	Mülheim a. d. R.	Saarbrücken
Potsdam				Hannover	Kassel	Recklinghausen	
Rostock				Düsseldorf	Dortmund		
				München	Trier		
				Kiel	Aachen		
				Hamburg	Wuppertal		
				Karlsruhe			
				Offenbach a. M.			
				Augsburg			

The two dimensional subspace simplifies the high dimensional data for illustration. The clustering result is shown by the example of two dimensions, each representing the share of buildings of a specific size and age, see figure 6. The data excerpt illustrates that FORMER GDR cities have a distinctively low share of floor area in single family buildings built between 1949 and 1978. The cluster AGED GIANTS has a slightly higher share in those buildings and a low floor area share in single family buildings built earlier, i.e. before 1920. The scatter graph shows that with these two building segments these two clusters may be exclusive explained. The differences in clusters that cover overlapping areas within this diagram may be described using a number of combinations of the 48 other building segments.

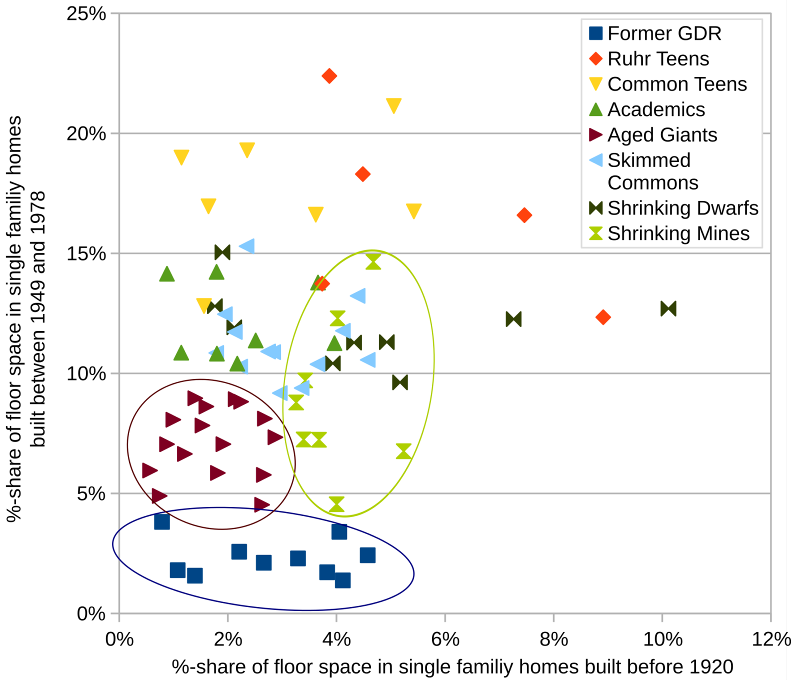
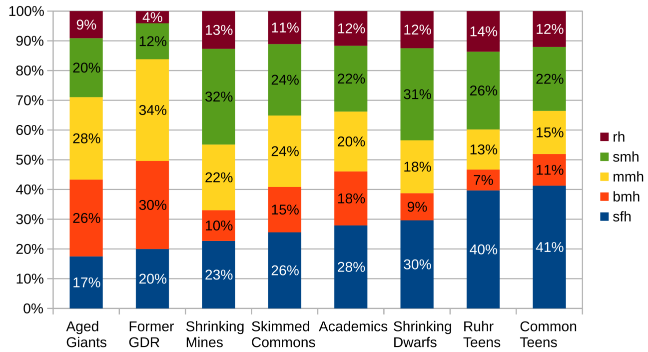
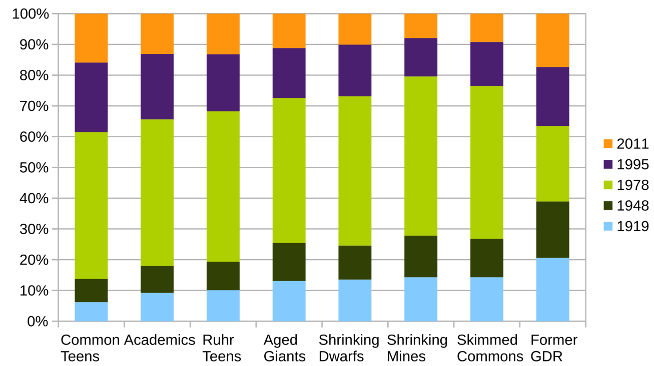


Figure 6: Two-dimensional clustering sample showing the shares of floor space in single family buildings built between 1948 and 1978 and built before 1920



(a) building category



(b) building age, indicated by the end year of building period

Figure 7: Building stock composition of the clusters by building age and size (category)

Due to their high floor area share in footnotesize, medium and big multi-family buildings[38] cities in some clusters likely have an energy advantage. Figure 7 (a) shows that the share of single family homes (sfh) varies between 41% and 17%, with AGED GIANTS and FORMER GDR cities having the lowest shares. On the opposite shares of big and medium multi-family homes are high within these clusters. This distribution is affects the energy consumption as single family homes have a larger surface to volume ratio and therefore higher transmission losses through the building envelope. In comparison, an energetic advantage rests with compact multi-family buildings.

The age distribution amongst the clusters also identifies the FORMER GDR cities as a special case. Figure 7(b) displays that the construction in period 1949 - 1978[39], i.e. after World War II, was significantly

[38] Abbreviations used in the figure 7(a): footnotesize, medium and big multi-family buildings (smh, mmh, bmh), single family homes (sfh), row houses (rh), compare also 2.3

[39] Labels within figure 7(b) correspond to the construction period end year, i.e. here 1978

lower within the GDR. As a result, the share of post war living space is about 25% within FORMER GDR whereas it reaches about 50% within all other city clusters. Although no generic conclusion can be drawn on energy performance, the post war buildings partly consume more energy per floor area and are more difficult to retrofit, due to thermal bridges. At the same time the share of low energy demanding, post reunification buildings within the FORMER GDR cluster is high, which should lead to a better energy performance of this cluster.

The building age structure has implication on the energy consumption. The energy demand of the buildings is assumed based on the buildings age, its size and attachment type. Size and attachment influence the volume to surface ratio with impact on energy demand. In the analysis of Aksoezen et al., 2015, buildings constructed before 1921 performed better than the average, whereas buildings built between 1947 and 1979, performed worse. This effect can be generalized for German cities, i.e. due to the recovery from the second world war living space was needed urgently and building material was scarce. Also in the following years the economies recovered and grew vastly, again increasing the need for living space especially in the cities. This urgent and increased need for living space caused fast solutions lacking quality and energetic performance.

As a second step within the overall methodology described in chapter 2.3, the projection of three policy paths draws energy futures that show the effect of different ambition levels in the renovation activity. These paths provide the energy demand developments necessary for a sensitivity analysis[40] of different saving levels to growth aspects as a contribution to the top level research question asking for the impact of growth. Therefore, they to open a bandwidth of energy savings at increasing political ambition levels.

To calculate these paths data on buildings, heating systems and renovation activity is needed, see chapter 4.1. With these information, the bottom-up building Model Invert/EE-Lab, see chapter 4.2, simulates the retrofit decisions that result in the final energy demand necessary for heating buildings in 2030, see chapter 6.1. A critical review of the model, the data and the assumptions concludes with an interpretation of the meaning of the policy paths in chapter 8.

4.1 Data need for the projections

The data need to calculate energy futures for heat in buildings depends on what details the output shall provide and which mechanisms or processes it shall cover. Therefore, the data need will be traced from the key outputs shown in table 6. These projection results enable the sensitivity analysis within the next step of the growth analysis in chapter 6.1. The outputs include the heated area per building, which was already used for clustering the cities, see chapter 3. Furthermore, the final heating energy demand of 2030 and 2008 is essential to provide the energy savings in 2030.

Table 6: data set provided for each building type

	unit	time	output
	$m^2{}_{building}$	const.	heated area
	kWh/m^2	2009	final heating energy demand
for each policy paths	kWh/m^2	2030	final heating energy demand (average across renovation mix)

While information on the present situation is largely available through empiric studies, it is the projections into the future that require the consideration of numerous underlying processes and assumptions. table 7 shows an overview of the different processes, their data requirements and the main information sources.
As the heat demand in a building depends on its floor area and the volume to surface ratio the building geometry is a central input for the energy calculation. The German building typology study, IWU, 2003, presents the German building stock based on 44 stereotypical building types. The details in this study include the geometry, the floor area and the number of buildings for each building type. This study is continuously updated by Diefenbach and Loga, 2011 and the database update in 2012 provided the data used in this research.

[40] The sensitivity analysis is included in chapter 6.1

Table 7: data set provided for each building type

output	information need	provided based on these data	source
$m^2_{building}$	geometry of the building	stereotypical buildings	Diefenbach and Loga, 2011
kWh/m^2_{2008}	energetic configuration in the start year of the simulation	geometry and energetic setup of the buildings	Diefenbach et al., 2010
kWh/m^2_{2030}	energetic configuration at the end of the simulation	renovation rate number of renovations	assumptions on current renovation rate energy concept[41]
		renovation depth energy saved per renovation	Diefenbach et al., 2016
		policy paths	current measures and assumptions[42]

As a contribution to the energetic configuration in the start year of the simulation, the building typology study also provides energetic details about the building envelope as the share of windows and the heat transfer coefficient of the outer hull. In 2010, the same institute published further data on past retrofit activity in Germany (Diefenbach et al., 2010). The data from this study were incorporated evenly into the data set in order to reflect the average state of the energetic modernization within the German building stock. As a result, the representation of the building stock within the data set reflects the renovation activities conducted before 2009, i.e. prior to the simulation period.

While the initial energetic configuration is delivered by a set of studies a number of assumptions need to be made to be able to project the energetic configuration at the end of the simulation period. On the one hand, these assumptions include more general but important aspects as the macro economy within price developments for energy carriers and technological solutions, see section 4.1.4. On the other hand, assumptions specific to the building's energetic development are needed, which are described within the following paragraphs.

4.1.1 Renovation rate

The renovation rate is one of the main drivers and barriers for energy savings in buildings as it is included within the national German energy goals to double the rate. The renovation rate sets the pace for the realization of heat savings as it determines the turnover of energetic building components. In a large and old building stock like the German one buildings have long lifetimes (Kalusche, 2004, p. 2) and are often used 100 years and more. Fortunate for energy savings, their envelope needs to be retrofitted earlier: after about 30 to 40 years (Kleemann and Hansen, 2005, p. 54). At these points in time, the chance arises to fix damages and more importantly to bring the building up to technical energy standards and comfort needs.

This means that on average once in 30 to 40 years, the energetic configuration of a building is changed. Afterwards, it is locked-in for another cycle as energy measures in between the technical renovation cycle are more cost intensive and thus in most cases economically not feasible. Subsequently, if the renovation event is not used to bring the energetic configuration to the desired level[43], the lost additional energy savings also take effect for each of the next 35 years.

[43] see next paragraph on renovation depth

Moreover, renovations are often postponed due to financial incapacity, gentrification and many other reasons (Achtnicht and Madlener, 2014; Stieß and Dunkelberg, 2013; Stieß et al., 2010). As a result of the increased envelope age, the energetic performance of the buildings declines.
The importance of the renovation rate was acknowledgement by the German government when it embedded the goal to double the rate in the energy concept. Within this concept, the renovation rate is estimated to be about 1% and targeted to increase to 2% (BMWi and BMUB, 2010, p. 5).

The renovation rate differs across studies due to missing comprehensive empirical data on how many buildings or m^2 of floor area are retrofitted in total. Hence, empirical evidence is collected in different studies on a sample basis (Feser, Vogt, and Winnige, 2015, p. 13). Friedrich et al., 2007, p. 9, for example, refers to renovation rates of 1.6% in 1994 and 2.2% in 2006. Stieß et al., 2010, p. 6 assesses the current rate at about 1% and claims an increase to 3% is technologically and economically feasible. Stieß et al., 2010 refers to Kleemann and Hansen, 2005, p. 58, who calculated a detailed technical renovation rate considering all building parts and construction periods separately. He also came to the conclusion that the renovation rate according to the component lifetime is 1.91% for staged renovations and averaged 2.57% for full renovations and compared them to a realized rate of 1.34%. Böhmer et al., 2011, (p. 7) assumes a renovation rate of 1.1% within their building model. BMVBS, 2012, (p. 9) assume a 1.4% renovation rate for their reference scenario. The KfW, 2011, p. 1 estimates an energetic renovation rate of 1.1% between 2005 and 2008.[44] Wietschel et al., 2010, (p. 142) suggests a renovation rate of 1.7% and differentiates an energetic renovation rate of 0.8%. In accordance with these studies, the current renovation rate is assumed to be around 1%.
The difference in the renovation rate of different studies may also arise from different calculation methods.

The calculation of the renovation rate, in general, compares how much was renovated to how much is there. However, there are two details to be defined in order to create a common understanding. Firstly, the rate may be based on the number of buildings or on floor area. Often, it reveals the share of buildings renovated in one year compared to the whole building stock but it can also be calculated as the renovated area in relation to the whole floor area, compare McKenna et al., 2013, p. 85. As multi-family buildings are much bigger than single family buildings this choice can have a significant impact. Secondly, a method for counting partial renovations needs to be defined. In reality, retrofits often cover a single part of the building as the windows, the roof or the walls. Hence, the building is retrofitted in stages. These staged renovations are more common mostly because financing multiple small investments over time is easier and due to the different lifetimes of the building parts.[45]

In this research, the renovation rate is based on the number of full building renovation equivalents. Partial renovations are aggregated to represent full renovation equivalents. Friedrich et al., 2007, p. 9, 65 uses the term full renovation rate.
This approach agrees with the definition of the renovation rate for the energy conservation of the whole building within the BMVBS, 2013, p. 26. Hence, the hull share of the renovated building component is calculated to obtain full building renovation equivalents.[46]

Furthermore, within the approach on hand the renovation rate represents an outcome of the simulation. The rate results from the construction period and a Weibull distributed lifetime of the building compo-

[44] KfW originally abbreviated the "Kreditbank für Wiederaufbau" which can be translated to "credit bank for reconstruction", which was its original purpose. Currently, the long form is not used any more.

[45] Attention should be paid to the compatibility of the staged measures advises Pehnt, 2010 in their newer policy suggestion. Especially, as the stages are spread over a long period of time it is helpful to plan ahead to arrive at the desired saving level and avoid incompatibility as well as errors.

[46] This definition deviates slightly from the definition within the German building typology that includes the weight of the component's energy saving in the calculation of the renovation rate. However, the resulting difference is minimal, see also BMVBS, 2013, p. 27

nents: roof, window, wall, and floor, cf. Müller, 2015, p. 82 and Pfeiffer, Fanslau-Görlitz, and Zedler, 2008. As a result of this approach, the renovation rate grows throughout the simulation time because the construction rate in the 60s and 70s rose triggered by the strong population growth.

Table 8 shows how the renovation rates develop for the three policy paths until 2030. The first path follows the "natural" lifetime of the building components whereas the second path is aligned with the goal of the German government to double the renovation rate (BMWi and BMUB, 2010, p. 5). The third path can be seen as an extremely ambitious scenario, which includes a renovation rates of 3% and more. These renovation rates are also used in various scenarios in Germany and Europe, see Hoier et al., 2013, p. 10 and Höhne, Sterl, and Fekete, 2015, p. 22.

Table 8: data set provided for each building type

scenario	2010 - 2020	2021 - 2030
current measures scenario 2012		
all retrofits	0.9%	1.8%
only energetic retrofits	0.8%	1.6%
climate protection scenario 80		
all retrofits	1.5%	2.0%
only energetic retrofits	1.3%	1.8%
climate protection scenario 95		
all retrofits	1.6%	3.2%
only energetic retrofits	1.4%	2.8%

4.1.2 Renovation depth

The renovation depth is counterpart of the renovation rate and indicates the energetic renovation effort. The rate provides the information on how many buildings are renovated, but only combined with the information on how ambitious these renovations are, can energy demand and savings be projected. As an indicator of the ambition level, the depth expresses how much heating energy will be saved for each renovation.

German standards for the renovation depth are based on the building code and defined within the context of the KfW subsidy scheme[47]. With increasing ambition level of energy saving measures the scheme offers higher subsidies as lower interest or grant. The scheme differentiates five renovation depth standards: KfW115, KfW100, KfW85, KfW70, KfW55 and the Monument standard. The KfW100 standard refers to the energy performance of a new building according to the current energy savings ordinance, the EnEV. Compared to this standard, a retrofit according to KfW85 needs to be planned to use only 85% of the KfW100 standard. The other standards are defined accordingly. The monument standard is defined for protected historic buildings. As these buildings are often required to preserve their outer appearance, their energetic renovation is technically and economically more challenging. The primary energy demand of buildings renovated by monument standard is, thus, not to exceed 160% of the KfW100 standard.

[47] https://www.kfw.de/inlandsfoerderung/Privatpersonen/Bestandsimmobilie/Energieeffizient-Sanieren/Das-KfW-Effizienzhaus/

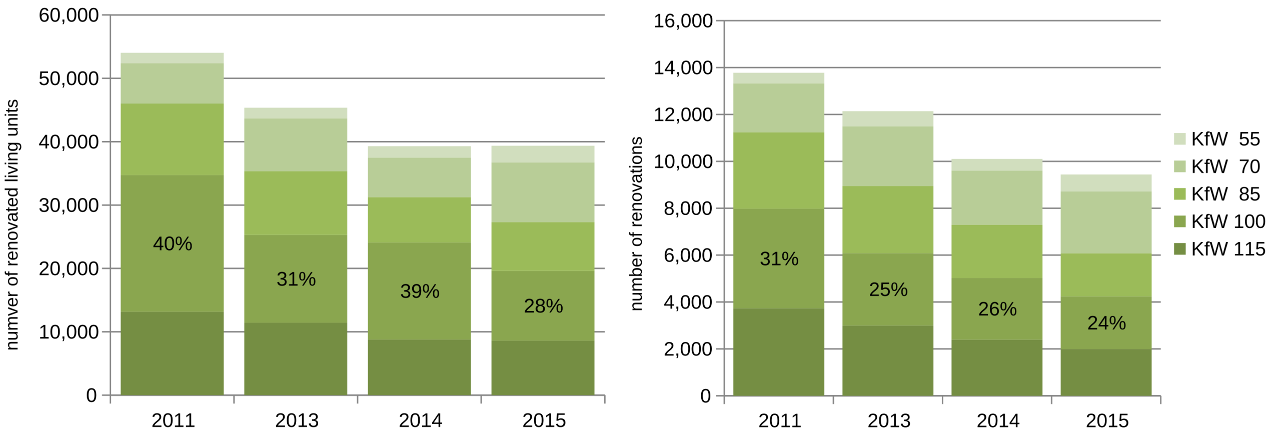
Different energetic measures are necessary to achieve the standards. A typical KfW115 standard renovation includes, for example, the installation of a condensation gas boiler with a solar collector for hot water, wall and roof insulation and windows with double glazing. Additional energy savings require an increased retrofit effort. For example, a bigger solar collector can support the heating system in order to achieve for the KfW85 standard. Triple glazing, special window framing and a wood pellet heating system is a combination that takes the energy saving to the highest standard within the scheme KfW55.

This subsidy program has supported energetic retrofit since 2006 and the program's evaluations show which standards have been applied. According to the monitoring reports between 2012 and 2016[48] a rather constant distribution pattern amongst renovation ambition levels, expressed as the subsidy standards of the KfW, can be observed in table 9 for different years. Consistently, the dominant standard is KfW100 applied in 30% to 40% of the retrofits. About 24% of the renovations represent the KfW115 and 20% the KfW85 standard. The ambitious standards are fulfilled by less and less renovations leaving KfW70 with 12% to 18% and KfW55 with a constant 5% of the measures.

Table 9: data set provided for each building type

year	KfW55	KfW70	KfW85	KfW100	KfW115	
number of subsidies cases granted						
2011	1,621	6,379	11,304	21,576	13,149	119,430
2013	1,696	8,332	10,055	13,860	11,418	221,080
2014	1,799	6,247	7,155	15,326	8,768	291,426
2015	2,629	9,442	7,681	11,003	8,604	411,259

Figure 8 illustrates that the share of the KfW100 standard is significantly higher for living units than for the number of renovations. This result indicates that big renovation projects with a large number of living units prefer this standard on an above average scale. A review for all standards and years reveals that 48.7% of the renovation cases shown in table 9 are better than KfW100 standard. This is only the case for 41.7% of the renovated living units, which indicates that smaller projects on average are conducted at a higher ambition level.



(a) number of renovated living units (b) number of renovations

Figure 8: renovation depth within the KfW subsidy program "energy efficient renovation"

48 Diefenbach et al., 2012, 2014, 2015

Within the approach at hand, the renovation depths is determined by the investor decision, i.e. the investor decides which ambition level will be realized. The investor faces four retrofit options. The first option is a maintenance with no energetic improvement. For a comprehensive retrofit this option is not compliant with the requirements of the German energy savings act, i.e. the EnEV . The second option is the standard retrofit and set at the minimum requirements of this savings act. Option 3 (R80) equals the KfW85 standard and Option 4 (R60) represents the KfW55 standard. Which option the investor chooses is influenced by the policy measures in place within the different policy paths.

4.1.3 Policy measures

The third building related assumptions are the policy measures implemented within the policy paths. Policy measures include market based instruments as subsidies, tax reductions for saving measures, additional taxes for fossil fuels. These measures emit r a monetary signal to the investor and stimulate energy savings and the use renewable energy.

In Germany, the predominant market instrument is the KfW subsidy scheme with several programs[49] supporting energy saving measures renovations in building. The largest program is "energy efficient renovation", which was provided with an annual budget of 1.8 billion Euro[50] for the past 3 years. The more energy savings are achieved the more subsidies are provided, in this approach the investor can choose between four renovation options: maintenance with no energetic improvement, standard renovation complying to EnEV requirements, the KfW85 standard, and the KfW55 standard. In addition to the renovation support, the market incentive program (German:Marktanreizprogramm (MAP)) provides financial subsidies for the use of renewable energy for heating.

As opposed to the pull effect of market instruments regulations push require investors to follow certain behaviour and punish non-compliance. The German building code, for example, requires investors who decide to retrofit parts or the whole of their building to achieve minimum standards. Embodied in the energy savings ordinance, these standards, set the maximum U-value that the renovated part of the outer hull should not exceed. In addition, the ordinance requires a certain percentage of the heat to be generated by renewable energy carriers. As a complement, numerous informational policy instruments essentially support the financial and regulatory framework by consulting and spreading the word. As a result, the impact of the policies cannot be measured separately and associated to one single instrument.

4.1.4 General assumptions

The investment decision reflects technical, economic and policy developments, as well as societal trends. As part of the technical progress, the input data include improvements of the technological solutions and a progression of their prices throughout the simulation period. Societal trends are as well parametrized in the model. The population growth and the demand for personal living space are considered within the calculation of the demanded living space in each year of the simulation.

49 "Energy efficient renovation", "Energy efficient construction", "municipal renovation"

50 See BMWi, 2017.

The development Germany as a whole, depicted table 10, shows a 10% growth in floor area whilst the population declines by 3%. The floor space consumption per person is assumed to grow to 47.5 m^2/cap, which is a moderate assumption compared to 51.5 that was suggested by Deschermeier and Henger, 2015, p. 23.

Table 10: population changes

		2010	2020	2030	change 2010 - 2030
living area	thousand m^2	3,338,139	3,540,738	3,684,870	+10%
population	million	80.6	78.8	77.8	-3%
living space per person	m^2/cap	41.4	44.9	47.4	

These assumptions include energy and technology prices as well as their development. These assumptions for the macroeconomic framework and were agreed with policy makers[51]. This includes the macroeconomic development, meaning population change, energy and technology price changes over time.
Table 10 shows the population development and the adjusted living area including trends for the increasing average floor space consumption per person.

Although the insulation material sector has been more innovative than other sectors, according to Sprengard, Sebastian, and Holm, 2013, p. 78 the market uptake is slow. They argue that the innovative insulation materials are thinner, more efficient and price increases are limited (Holm and Sprengard, 2013).
Sustainability and environmental issues appear for insulation materials especially in the stage of renewal and deconstruction. As layed out by Dunkelberg and Weiß, 2016, p. 10, insulation and cannot easily be separated leaving it as a composite waste that can only be combusted. Additionally, due to brominated flame retardants that are included in installed insulation[52] the incineration needs to include waste gas cleaning to filter the resulting brome containing salt. The disposal of waste material predominantly means burning it, which is not resource efficient and will release a CO_2 as it is made of oilMäurer and Schlummer, 2014 .

[51] These agreement discussions were part of the project Klimaschutzszenario 2050, see Repenning et al., 2014 and BMWi and BMUB, 2010.

[52] Brominated flame retardants were banned in 2013, see Umweltbundesamt, 2013.

4.2 Simulation of energy demand with INVERT/EE-Lab

The introduced data feed into the bottom-up building model INVERT/EE-Lab, which was selected to project the development of the heat energy demand. A number of models allow this projection, INVERT/EE-Lab was chosen, as it includes a bottom up simulation of the investment decision for retrofit and facilitates the implementation of multiple energy policies. Hence, the model can reflect the impacts of the different policy paths on the energy demand. Moreover, it offers the functionality to assess the impact of policy pathways on a bottom up building level, i.e. with the specification of different building types. This chapter lays out how the possible futures were calculated with a focus on how policy measures change the investment decision.

INVERT/EE-Lab simulates the building stock's development on a disaggregated level with stereotypical, one-zone buildings that are equipped with energetic envelope features and heating system features. In case of Germany, about 1200 equipped stereotypical buildings are defined and extrapolated to represent the German building stock according to Diefenbach and Born, 2007. To emulate the building stock's changes over time, the simulation includes the construction, the destruction, the renovation activities, and heating system changes. Underlying each energy saving measure an investment decision chooses amongst available investment alternatives. In each simulated year, INVERT/EE-Lab first calculates these investment decisions for one of four possible energetic retrofit options. It then computes the energy demand by building segment. In the end, the energy savings are calculated by subtracting the specific energy demand in 2030 from the initial one. An in-depth description of the model provides Kranzl et al., 2013.

4.2.1 Simulation of the investment decisions

The investment decision is applied to two types of energetic measures: the retrofit of the envelope and the renewal of the heating system. Usually, these measures are due separately at the end of each lifetime. These cases, where building parts reach the end of life and need to be replaced or retrofitted are identified within each time step of the projected period. The affected building segments[53] are owned by a mix of defined investor agents. Single family buildings, for example have a large fraction of private owner-occupiers, while multi family buildings are mostly owned by a housing corporations and associations. Each of these investors have a set of weighted criteria. They consist predominantly of financial factors as investment sum and net value but also include comfort and sustainability aspects.
In detail, each investment decision incorporates the following aspects.

- The buildings are owned by defined variety of investors with different investment criteria and as a basis for their behaviour.
- This investment behaviour results in the selection of a technological solution. Each solution represents contains a set of decision relevant properties, i.e. investment, energy cost savings, payback period, sustainability, and comfort. These properties serve the investors decision criteria.
- Each investor possesses a set of weights for these decision criteria. The criteria consist predominantly of financial factors as investment sum and net value but also include comfort and sustainability aspects. The weight was determined by a panel survey of experts described in Steinbach, 2016, p. 21.

[53] Buildings with same size, age, envelope quality and heating systems are modelled in groups called building segments.

- The combination of the technological solution's properties with the investor specific weight represents the benefit of the solution for the investor. A Nested-Logit approach as described in Steinbach, 2016, p. 100 and Müller, 2015, p. 111 then distributes the solutions across the buildings that are subject to this investment decision.

The weakness of this approach is, that it is not based on a large empirical base of executed investment decisions. However, the approach was validated to suitably replicate the energy development.

4.2.2 Influence of policies on investment decisions

Policy measures that are designed to influence the investment decision are modelled to the desired choices more attractive by financial means or restrict the choices through miminum requirments. A tighter building code, for example, requires a certain u-value for external walls. Compliant retrofit choices subsequently lead to higher energy savings. An increase in the budget and subsidy rates for KfW[54] incentives reduces the financing need of the investor. In the same manner, the policy measures for heating systems consist of a requirement and a financial subsidy. The renewable energy law (German: EEWärmeG, Bundesregierung, 2015, 2008) requires a quota of renewable energy use when (a) a new building is constructed, (b) a building is retrofitted and (c) the heating system is changed. The increase of the renewable energy quota as well as the introduction of triggers (b) and (c) narrows the range of suitable solutions available for the investment decision within the model. As a part of the renewable energy law (glseewaermeg), the market incentive program [55], grants funding for investments in renewable heating systems and thus improves their financial criterion for the investors' decisions.(Steinbach, 2016 and Müller, 2015)

For the projection of the energy policy pathways BAU, CP80 and CP95, the policy measures are defined with an increasing ambition level, shown in table 11. For example, the minimum requirements for the energy retrofit defined within the BAU scenario are based on the current building code (EnEV : BMWi, 2013). Within the CP80 scenario they are 30% more ambitious to be increased by another 20% for the CP95 scenarios. This increasing ambition is accompanied by rising levels of financial subsidies for retrofits and renewable energy. With respect to the use obligation for renewable heating and different The policy paths were designed in alignment with energy and climate goals set by the German government set within the energy concept (BMWi and BMUB, 2010). Thereof, the pathways reflects the political goal to double the retrofit rate[56].

[54] cf. chapter 4.1.2
[55] http://www.erneuerbare-energien.de/EE/Navigation/DE/Foerderung/Marktanreizprogramm/marktanreizprogramm.html
[56] implemented in CP80 and CP95

Table 11: policy measures parametrized within the different policy pathways

policy pathway	parameter	value and description
KfW program: energy efficient renovation		
BAU	annual budget	1,000 million Euros from 2012 until 2024,
	subsidy fade out	starting in 2025 at a 10% rate per year
	share granted	12.50% for KfW85 and 20% for KfW55
CP80	annual budget	2,000 million Euros from 2015 until 2030,
	subsidy fade out	starting in 2031 at a 5% rate per year
	share granted	18.75% for KfW85 and 30% for KfW55
CP95	annual budget	increase to 4,000 million Euros until 2020,
	subsidy fade out	starting in 2031 at a 5% rate per year
	share granted	18.75% for KfW85 and 30% for KfW55
KfW program: energy efficient construction		
all	annual budget	0.5 billion Euros
Market Incentive Program (MAP)		
BAU	annual budget	0.3 billion Euros
CP80		0.6 billion Euros
CP95		0.6 billion Euros
ENEV: energy savings ordinance including the German building code		
BAU	retrofit requirement	KfW 140
CP80		KfW 100
CP95		KfW 80

This chapter contains the presentation of the results including the development of the average energy demand until 2030 for the three three policy pathway with their increasing ambition level. The energy demand for heating per m^2 is the basis for the assessment of the impact of population growth in the next chapter. It results from the mix of energy improvement measures at the building envelope. It contributes to the goals defined for each pathway at final energy demand level in 2050. Table 12 shows this energy demand for the three calculated policy pathways averaged across all building types, sizes and ages.

Table 12: projected energy demand for the policy pathways

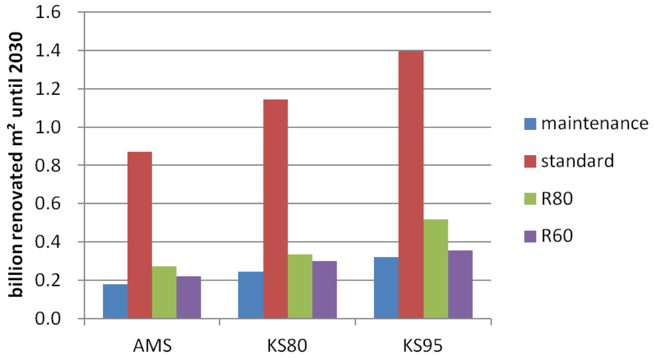
	average final energy demand	
	2010	2030
BAU	180 kWh/m^2	135 kWh/m^2
CP80	180 kWh/m^2	110 kWh/m^2
CP95	180 kWh/m^2	90 kWh/m^2

Bettgenhäuser, 2013, (floor area projection on page p. 139, final energy demand on p. 145) projects a result similar to the CP95 Scenario in his Fast Renovation scenario. The ratio of his final energy demand and floor area projection for 2030 suggests 76.7 kWh/m^2 as specific final energy demand, while he is starting out at 173.1 kWh/m^2 in 2012. The different specific energy demands result from different renovation behaviour. On the one hand, this renovation behaviour is affected by the policy measures described in chapter 4.1.3. On the other hand the ageing building stock is assumed to require an increased renovation activity 4.1.1.

Within the first policy pathway the renovation depth, cf. 4.1.2, for the standard renovations remain at the level required by the current building codes in the energy savings ordinance enacted in 2014 (German: EnEV). Within the investment decision, this required renovation level (standard) forms one of four renovation alternatives the simulated investor can choose from. Two alternatives add to the standard renovation: R80 and R60 are 20% and 40% more ambitious than the standard retrofit. These renovation options are used within the investment decision process. The simulation results for 2030 in figure 9 show, that about 18% of the floor area has been renovated on a standard level in policy pathway 1. On average these buildings consume 95 kWh/m^2.

The second policy pathway includes the strengthening of the building code in 2020. As a result, the maximum allowed u-value of the standard renovation decreases by 20%. Subsequently, the u-values of the renovation alternatives R80 and R60 are reduced accordingly. Within the third policy pathway, these steps towards more ambitious renovations are tightened even more.
Table 9 shows the different shares of each renovation alternative within the of policy pathways and the resulting the average energy demand.

In addition to the renovation depth, the renovation rate varies across the policy pathways, cf. 4.1.1. As proposed by Hansen, 2009, p. 39, Müller, 2015, p. 83 implements the renovation rate as a result of the age structure of the building stock in INVERT/EE-Lab. Thereby, he considers the technical life of the



(a) number of renovations

	main-tenance	standard	R80	R60	Total
share of floor area renovated until 2030					
AMS	3.7%	17.9%	5.6%	4.5%	31.6%
KS80	5.0%	23.5%	6.9%	6.2%	41.5%
KS95	6.6%	28.7%	10.7%	7.3%	53.3%
each option's share of renovated area					
AMS	12%	56%	18%	14%	100%
KS80	12%	57%	17%	15%	100%
KS95	12%	54%	20%	14%	100%
average final energy demand for heating in kWh/m²					
AMS	152	95	81	51	0
KS80	141	91	82	47	0
KS95	138	87	79	46	0

(b) renovation depth and share

Figure 9: renovation depth and rate for each renovation option in the different scenarios

building components forming the building envelope. Subsequently the renovation rate follows a natural growth between 2010 and 2040 in pathway BAU. In pathway CP80 and CP95 an additional increase of the renovation rate is assumed, which is modelled as a reduction of the technical life of the envelope as described in section 4.1.1. All of these parameters set the point in time for the renovation of one modelled building.

In contrast, the decision about the renovation depth is simulated internally for each renovation decision according to Steinbach, 2016. Figure 9 shows how the investors react to the different renovation alternatives. A big difference across policy pathways can be observed for the renovation rate. The number of renovations shows a big difference between the policy pathways whereas the shares of each option differ marginally. The majority of renovations are on the minimum requirement level, i.e. standard, barely 20% at 80% of that and about 15% at only 60% of the standard U-Values. The maintenance option counts renovations with no energetic improvement. With regard to the EnEV these are either not subject to minimum levels or not compliant. The share of maintenance renovations remains steady at 12% across the pathways. The biggest shift across policy pathways can be observed for the share of R80 renovations which grows from 18% to 20% comparing pathway 1 and pathway 3.

Do the policy pathways provide a prognosis the future? No. They are generated with the help of a INVERT/EE-Lab that by the nature of a model simplifies the reality to answer the research question. For this assessment, it is used to generate energy demand and investment trajectory under the influence of a variable set of policy instruments for the assessment on hand. The model includes factors that are relevant to answer these questions. In this case, the model focusses on the development of the heating energy demand for buildings under different renovation activity levels. Therefore, the main factors are the building mix in the stock, the energy mix in the heating systems and the policy mix influencing the renovation activity. Unconsidered remain the income level or the age of the investor that may change over time and influence the renovation decision. The pathways do not need to reflect future developments. For the use within the work at hand their comparability is relevant and given as the pathways are based on the identical assumptions and approach.

Further limitations to the accuracy of the policy pathways originate in data availability issues. The rich variety of the real building stock can only be modelled as a composition of about 40 stereotype buildings. Based on these, the renovation options are modelled and leave out specialized measures necessary to retrofit the individual, real houses in all their architectural finesse.

Additional factors that impact the policy pathways but were not included within the calculations at hand include the geographic breakdown of Germany, different climatic conditions, the socio-economic background and income of the investors. While the investor mix including the decision preferences of each investor group has been included Steinbach, 2016, p. 21 and remains constant, in reality, income levels or age of the investors change over time and influence the renovation decision. The effects present opportunity for future research.

Furthermore, the analysis is not embedded into a macro economic environment with various consequences. Firstly, the restrictions for renovation arising from the limited availability of trained workforce and to perform the renovations. Secondly, there is no mechanism embedded to reveal shortages for materials necessary to conduct these renovations. For both, material and workforce, the effect of more and deeper renovations are note modelled.

Deep energy retrofit includes advanced and more sensitive technology and thus requires planning expertise and qualified craftsman to avoid damage to existing buildings. Garrecht, 2009 points to the risk of creating constructions that are critical from a perspective of building physics, if maximizing the energetic performance is the sole focus of a renovation. He argues, that thermal-technically retrofitted building envelope components pose a interactive heat and moisture system under the influence of daily and seasonal changes in outdoor climate. Due to the complexity of this system and the compound composition of the building parts an assessment with simulation calculation is necessary to ensure building physical functionality.

The increase of the renovation rate[57] may give reason for discussion, as in BMVBS, 2013, p. 27. Although, the building age and the lifetime of the components may impair the envelope quality, the owner decides

[57] cf. 4.1.1

whether to renovate and when, which may deviate from the model assumptions. In fact, the delay[58] of renovations is a known problem. Kleemann and Hansen, 2005 calculated the expected renovation rate based on the Weibull distributed technical life of building components. They compared it to an empiric survey and found a lack suggesting renovations are in reality delayed. How many buildings are subject to a delay cannot yet needs empirical assessment. How much the renovation rate can be raised by a catching up on delayed retrofit remains unknown as the delay is unknown.
The pathways provide a bandwidth of possible energy futures for heat in buildings, which serves their purpose as an input for the quantification of how different energy developments react to growth.

Whether the CP95 pathway is a realistic scenario or an idealistic utopia it can certainly provide an best case for the energy development within the building stock. Room for discussion is certainly provided by the very high renovation rate and the very ambitious renovation. On top, these two developments are combined, which denies the fact that more investors postpone retrofits when requirements tighten. Even when doubling the financial support, the shift towards most ambitious retrofit does not take up speed. However, there are still 14 years to go until 2030 and may be some technological breakthrough will fire on the development to get conventional combustion out of our heating supply.

The current policy scenario scenario, however, cannot be considered a worst case as it includes the implementation of current German building code and the renovation rate remains within its natural age driven cycle. While the building code is ambitious compared to other European countries with similar climate (Atanasiu et al., 2014, p. 66) compliance in its implementation is a substantial effort for the investors. Hence, experts consider it highly depend on controls (see Bürger et al., 2012, p. 79 , Schlomann et al., 2012, p. 117 and Bürger et al., 2013, p. 53), that are not currently in effect.
Although a policy pathway with more energy demand is possible, the spread of the scenarios is sufficient for the sensitivity analysis.

[58] A renovation is delayed when a building age exceeds the technical life of its components without them being properly replaced.

The population growth leads to a higher heating demand for the additional floor space used by the additional people. However, there are more indirect effects which are triggered, for example, by the availability of residential buildings and the capability and limits of the city to grow accordingly. Additionally, the rental and real estate market may react to a change in demand for floor space. The following chapter lays out the processes initiated by population growth, identifies and quantifies the key drivers for a growth related change in heating demand in buildings.

The next section (5.1) will review the parameters of the heat demand calculation in order to derive those parameters that appear to be driven or influenced by population growth. The goal is to find which factors within the heat demand calculation may be influenced by population growth. In the following section (5.1.2), these factors are then discussed within the context of growing and shrinking cities to create a storyline and hypothesis on how growth may affect these energy drivers.

5.1 Method for identifying the growth factors

To assess the impact of population growth on heat demand in buildings[59] growth related processes with heat demand effect will be identified. To determine which processes potentially have an effect on heat demand, its calculation parameters are reviewed. The standard DIN V 4108-6:2003-06, p. 15 specifies its calculation as follows:

Table 13: current German norms involved in the calculation of heat demand in buildings

id	version	name
DIN 4108-2	2013-02	part 2: minimum requirements for heat preservation
DIN 4108-3	2014-11	part 3: climate related humidity protection: requirements, calculation method and guidelines on planing and implementation of heat preservation.
DIN 4108-4	2017-03	part 4: design values for heat and humidity preservation
DIN 4108-6	2004-03	part 6: design values for heat and humidity preservation
DIN 4108-7	2011-01	part 7: air tightness of buildings - requirements, recommendations and examples for planning and implementation
DIN 4108-10	2015-12	part 10: application related requirements for factory produced heat insulation materials
DIN V 18599-2	2016-10	part 2: useful energy or energy need for heating and cooling of building zones
DIN V 18599-5	2016-10	part 5: energy demand of heating systems

Table 14: population, floor area per person and their changes between 2005 and 2011 in Germany's big cities

heat demand	= heat losses	$-$ heat gains
losses	= transmission losses (L_{trans})	+ ventilation losses (L_{vent})
gains	= internal gains (G_{int})	$-$ solar gains (G_{sol})

5.1.1 Heat demand calculation

$$losses = \sum\left(\frac{24}{1000}t(\vartheta_i,h-\vartheta_e)*\left(\sum_{k=0}^{K}(f_kA_kU_k)+\rho_Lc_pf_{hV}A_{gfa}hn_l\right)\right) \tag{10}$$

$$gains = \eta_h\left(\sum(f_{hV}q_{i,h}A_{gfa})+\sum_{j=1}^{t}I_{s,j}\sum_{b=1}^{B}(A_wS_{hor}S_{vert}S_{hig}S_{sha}F_{fr}F_{orth}g_w)\right) \tag{11}$$

k	building part
t	number of days of the month for the calculation of the mean monthly values
ϑ_i,h	internal temperature, dependent on user profile (h)
ϑ_e	external temperature, dependent on climate
f_k	temperature correction factor, dependent on building part and adjacent substance (air, earth)
A_k	surface area of the building part
U_k	U-value of the building part
ρ_L	density of air at 15 °C
c_p	heat capacity of the air
f_{hV}	transformation factor for obtaining the heated and ventilated net volume from the outside measurements that describe the gross volume.
A_{gfa}	gross floor area
h	room height
n_l	air exchange rate
$q_{i,h}$	mean inner (i) heat gains dependent on user profile (h) in W/m^2
$I_{s,j}$	mean, monthly solar radiation in W/m^2
A_w	window area in m^2
$S_{hor}S_{vert}S_{hig}S_{sha}$	shading factors: horizontal, vertical, for increased horizon, for permanent shading
F_fr	factor for window glas reduction for frame
g_w	total amount of energy transmission through glass (g-value)
F_{orth}	factor for non-orthogonal solar radiation
$frac241000$	conversion factor from Wd (Watt days) per month to kWh/month

Table 15: parameters for the cacluation of heat demand according to current German Norms

The next paragraph discusses the main parameters and whether they can be influenced by the population development.

- Volume ($A_{gfa}*h$) and Surface ($\sum_{k=0}^{K}A_k$) of buildings have a big influence on their transmission and ventilation losses. In national building stock descriptions, these two are often parametrized in building types and the overall heated area.[60]

- The energy performance of the building is predominantly expressed in the U-value (U_k) of the building parts (k). Within this analysis, the U-values for the buildings parts are varied by the

[59] The heat energy demand depends on the heat demand, which is determined by the energetic construction of the building, and the heating equipment (heat supply system and distribution system). This analysis does not consider the heating equipment.

[60] Examples for the building type are single-family home (sfh) and multifamily home (mfh).

different renovation activities defined in each the policy paths in chapter 4. This approach indirectly includes the assumption that the renovation activity is not significantly influenced by population growth. In contrast to this assumption, the economically weak situation in shrinking regions may defer or delay investment intensive renovations. As empirical validation is still outstanding, this research will need to satisfice with growth independent renovation activity as a simplification(see discussion on page 72).

- The user's heating behaviour essentially impacts the required indoor temperature (ϑ_i, h) and thus indirectly the duration of the heating period. Within this analysis the indoor temperature is also varied in the policy paths. Within the ambitious scenario, it is reduced by one degree on average as a sufficiency measure.
- Solar gains are mainly dependent on the geographic location and hence assumed to be independent of the population growth.
- internal gains are not included as a growth dependent factor. Although in a growing city the average income level may be higher, which may affect the average equipment rate of households with electronic devices but also increase the distribution of efficient appliances. Another part of the internal gains is contributed by the inhabitants themselves and thus dependent on the number of inhabitants and the mean stay within the building. In addition, the internal gain is dependent on the use and user of the building. As a result, the internal gains are not included in the quantification but in the qualitative discussion of this analysis.

Subsequently, the heated area and the building type remain as parameters for analysing the impact of population growth on energy demand and energy savings.

5.1.2 Rationale and expected impact of heat demand drivers

The Growing City remains omnipresent a result of the "megatrend" urbanization. Most German cities experience an ongoing growth 23. What happens to buildings and their energy demand when the population in a city grows? The demand for living space is mainly driven by the population count. For each person though it is likely influenced by the income and the cost of other goods as food and possibly energy (for heat and required job mobility). The family development is also a contributing factor, a when kids grow up and move there is a tendency for parents to keep the residential unit. The composition of the population lays out the preconditions for the future change. Cities with a large share of students and old people, should already have a high per capita floor area uptake and which may not increase as much as the average. Whereas, cities with an above average share of families potentially shift stronger towards more floor area per person (m^2/cap).

1. The additional people need a place to live, thus the floor area demand rises. In case the population grows slowly and the supply of living space can grow accordingly, the floor space demand per person remains constant. However, the supply of additional living space may impaired by construction restrictions. Within its sustainability policy, the German government has set to the goal to limit the surface sealed to 30 hectare[61] . Land management bodies evolve new ways such as inner development to efficiently use space, see Zwicker-Schwarm et al., 2008. However, new floor area may not be available as fast as the population grows. Schiffers, 2009, p. 31 argues that due to long and capital intensive construction processes the supply reacts much slower than the demand, which in turn leads to living space shortage.

[61] 1 hectare equals 10.000 m^2 per day until 2030, see Bundesregierung, 2016a, (p. 159) and Umweltbundesamt, 2004, (p. 7)

2. This shortage of living space intensifies the use of space also called the use intensity (m^2/cap). In other words, the population density rises as more people live in the same amount of floor area and surface area.

3. As a direct market reaction, floor area shortages increase its price according to the price determination in a competitive market economy, also compare Rohr-Zänker, 2014, (p. 2). This market mechanism creates an additional incentive to share apartments and increase the use intensity. On the other hand, high prices are one of the top arguments to move from the centre to the vicinity of a city, compare Günthner, 2012, (p. 75).

4. The intensified use of space may increase the heat demand, as rooms that were not used before may not have been heated or kept on a lower temperature discussed as partial heating on page 64. This effect can only be included in a qualitative discussion, as research on behaviour change related to increased floor area per person is not yet available.

5. In growing cities new building construction has three effects. Firstly, it adds energy efficient floor space to the building stock mix, that decreases the average energy demand per m^2 of the building stock.

6. Secondly, new construction simply adds heated area to the buildings stock. It is likely being occupied (and heated) due to its attractiveness and the released market prices. Due to the tight market, the living space that is freed up in existing buildings is also being used. Therefore, the total energy demand will increase.

7. Thirdly, there are controversial effects on the market and thus on use intensity (m^2/cap). As it offers additional living space, new construction increases the supply so the same number of people now have more space to live in m^2/cap. On the market, the new construction releases the shortage, and may relax the prices, which affects all the population in the city and reduces the incentive for fewer floor area uptake m^2/cap. However, the additional living space may be more attractive and hence, keep the elevated price levels.

The Shrinking City is scarce in Germany. Most of them are located in the east, however, single cases are spread throughout the country. What happens in shrinking cites?

1. Shrinking household sizes: young people have a high residential mobility for many years, compare Rohr-Zänker, 2014, (p. 3). People move to other cities to find fitting opportunities to study or work Spars, 2012, (p. 52, p. 62). The education related migration applies to young adults that recently finished school and likely move out of their parents home into another city to study. As a direct result, this migration will cause household sizes to shrink. Secondly, as an example work related migration includes the migration of a (young) family where one partner has found a job elsewhere and the family moves together. As families usually have an above average household size, them moving away also decreases the average household size.

2. As a consequence of the reduced average household sizes, under the precondition that in an existing building stock the geometry of residential units cannot be adjusted immediately, the per capita floor area must increase.

3. The effect of parents remaining within the family home when children leave is called the remanence, according to Mackensen, 2007, (p.319). This effect results from the declining residential mobility that sets in with age (Rohr-Zänker, 2014, (p. 3)). As a result the population of shrinking cities ages.

4. Due to the population decrease, the vacancy increases. According to mainly in buildings with little reachability, low energy quality, unsuitable living unit size and spacial design locations, mainly in multi-family buildings.(Simon-Philipp and Hopfner, 2013, (p. 28, p. 34) and Braun, 2010, (p. 25))

5. As a result of the relaxing housing market relaxes the prices drop equivalent to the case of Leutner et al., 2011, (p. 3) and Deschermeier and Henger, 2015, (p. 23). The effect of remanence effect and more affordable living space stimulates the per capita floor area (m^2/cap) to increase.

6. Subsequently, with the m^2/cap the heat demand per person rises. The heat demand per person is likely to increase less than the living space per person, as unused space may not be heated fully. However, even if it is heated only slightly, it is still an addition to the previous heat demand.

7. New building construction will be lower than average, as there is a lower need for new construction as existing buildings are available. However, the existing buildings may not fit the needs, which may induce new construction, compare Effenberger, Banse, and Oertel, 2014, p. 19. The average energy demand per used floor space will improve in the same manner as for the average building stock.

How much space does a person need? What type of buildings do they choose? Are the answers to these questions different when a city grows as opposed to when a city shrinks? As a basis for a detailed analysis to obtain reliable answers, a regression analysis is performed on population growth and floor area demand.

5.2 Analysis of floor area demand via regression analysis

The regression analysis is used to derive the functional correlation between an independent and a dependent variable. Firstly, the correlation between growth as the independent and living space as the dependent is assessed. Secondly the dependency of prices on growth is analysed. While the first regression serves as an assumption for the projection of the energy savings development, the latter analysis seeks to explain that relationship with market behaviour.

5.2.1 Background and goal of the regression

What is the rationale of the correlation assumption? It is used to identify the correlation of the population growth between 2005 and 2011 and the change in per person floor area in this city between 2004 and 2010[62]. The assumption is that the correlation can be described by a linear function. In detail, a cities growth will result in a diminished living space per person demanded. Content wise, the linear correlation assumption is based on two aspects. Firstly, an increased number of people is faced with a given living space that may adjusts but only slowly. The barrier for growing living space are a temporal delay for the construction process itself and policy measures to avoid the sealing of further surfaces. Secondly, the increased demand and the inflexible supply lead to an increased price level.

What is the outcome of the regression? The goal of the first regression analysis is to derive a functional correlation between population growth and floor area demand. Therefore, the regression facilitates to determine how the floor area demand per person was affected by population growth in the past. Based on this historic behaviour the probable future correlation can be derived. The future development of floor area demand has a significant impact on the development of the energy demand in 2030, which is the main outcome of the total analysis. Hence, the functional correlation serves as an assumptions to determine the future floor area demand based on population growth. This is the deliverable of the regression analysis for the total analysis.

What is the regression result used for? This method was chosen to describe the impact of population growth on the floor area demand per person in an equation, to be able to integrate that influence into the projection of energy demand. The equation delivered by the regression analysis reflects how the floor area demand per person changes with a certain growth in the population. The following paragraphs describe the formal steps in building a regression model and how it is applied to the described data.

The following steps form the regression analysis including the validation of its results.

1. The scatterplot allows a first visual assessment of the correlation. The diagram gives a impression on the correlation of the dependent and independent variable. Based on the distribution of the data points the scatterplot indicates whether a linear correlation would describe the data well. In addition to identifying outliers, it indicates whether the variables are positively or negatively correlated.

[62] Data for exactly matching time periods was not available, however, the overlap appears adequate.

2. In addition to the visual assessment the strength of the correlation and thus, the explanatory strength of the regression line is evaluated with the statistical indicators, (a) the coefficient of determination, (b) the standard error of estimate and with the (c) the F-test.

3. A first indicator of the strength of the correlation is the coefficient of determination. It lies in the range $[-1..1]$. A strong positive correlation is accompanied by a coefficient close to 1, and a strong negative correlation is accompanied by a correlation of nearly -1. As a result, when the correlation coefficient is close to 0, the correlation is weak.

4. Another indicator for the strength of the correlation is the standard error of estimate (SEE). It expresses the variation in the residuals, i.e. the deviations of the data points from the regression line. Compared to the standard deviation of the data points the SEE gives information on how much the regression describes the data.

5. The F-test validates the hypothesis that the variance of the residuals and the variance of the regression are independent and randomly distributed and thus provides evidence to approve the model used for the regression.

6. Finally, the regression model is used to project the analysed parameters, as for example the floor demand, into the future. This step provides conditions and limits, as well as assumptions, an and approach for these projections.

Sample and sample space give a first statistical perspective on the data and facilitate setting up the regression model. Firstly, the sample and how it is selected are reviewed. The approach on hand selected 76 cities systematically by geography (German cities) and by size (>= 100.000 inhabitants). Hence, the sample is not random and conclusions cannot simply be extrapolated to other cities of different sizes and in other countries.

Secondly, the sample space is explored. The point in time of the data collection, 2011, additionally describes the state in which the cities were (ω). This state is influenced by events that happened previously. Hence, the state is one , called ω out of all possible states (Ω). This perception will help to handle the unexplained variations from the regression line.

Finally, a perspective on calculated statistics and their properties is given. For the understanding of a regression analysis and its value it is important to know the expected value, the distribution and the variance of all calculated values. These values serve as the basis for analysis on the goodness of fit and on the significance of the regression model. To differentiate these two, the goodness of fit indicates how well the regression line fits the data. In Addition, the test for significance of the model[63] describes how much of the information that is in the data is included by the regression line.

Regression model consist of parameters and a number of assumptions their distribution, variance and expected values. The following paragraph provides an introduction to linear regression and the notation used in this work. Let X_i and Y_i be random variables. These variables are analysed assuming a linear correlation of the function $E[Y_i|X_i] = \beta_0 + \beta_1 X_i$. The linear correlation possesses two parameters: the intercept β_0 and the slope β_1.
According to Chatterjee, Handcock, and Simonoff, 1995, Mosler and Schmid, 2011, p. 293, Urban, 2011, p. 49 and Brannath and Futschik, 2001, p. 186, the deviation of the data points from the regression line are called residuals (U_i) and included in the regression model: $Y_i = \beta_0 + \beta_1 X_i + U_i$. One assumption is,

63 In this analysis the F-test is used.

that these residuals are randomly, i.e. normally distributed, if the regression line sufficiently describes the correlation of the variables. Furthermore their variance is independent of the independent variable X and of the sample i. As the regression line minimizes the sums of squares of the data point distances to the line, the expected value of the Residuals is zero: $E[U_i] = 0$. These assumptions about the residuals can be formalized as: $U \sim \mathcal{N}(0, \sigma^2)$. All of the described assumptions form the model:

$$\begin{aligned} Y_i &= \beta_0 + \beta_1 X_i + U_i && \text{für i=1,...,n} mit && (12) \\ U_1, ..., U_n & && \text{gemeinsam nomalverteilt mit} && (13) \\ E[U_i] &= 0 && \text{für i=1,...,n} && (14) \\ Var[U_i] &= \sigma^2 && \text{für i=1,...,n} && (15) \\ Cov[U_i, U_j] &= 0, && \text{für i,j mit i} \neq \text{j} && (16) \end{aligned}$$

From these assumptions, Mosler and Schmid, 2003, p. 300 concludes a normal distribution of the dependent variable Y_i as well as its expected value and its variance:

$$Y_i | X_i \sim N(\beta_0 + \beta_1 X_i, \sigma^2) \tag{17}$$

Regression coefficients are now estimated to minimize the squared distances of the collected data points to the regression line. As they are based on the data points, the results do not represent the true values, but estimates. Hence, they are named differently and β_0 is estimated with $\hat{\beta}_0$ and β_1 with $\hat{\beta}_1$. As statistics based on the data points, these estimates possess an expected value, a distribution and a variance. Many possible approaches exist to estimate β_0, β_1 and were were analysed and tested by statisticians in the past. As a result, the best known estimates are used to approximate the regression coefficients, with their distribution, expected values and variance delivered in Mosler and Schmid, 2003, p. 294:

$$\hat{\beta}_0 = \bar{Y} - \hat{\beta}_1 \bar{x} \quad \text{or simplified} \quad a = \bar{y} - b\bar{x} \tag{18}$$

$$\hat{\beta}_1 = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \quad \text{or simplified} \quad b = \frac{cov(x, y)}{var(x)} \tag{19}$$

In addition Mosler and Schmid, 2003, p. 300 provides the expected value and the distribution of the variance of the estimates, which are used for the further tests, as the F-test which analyses the explanatory significance of the model.

$$\hat{\beta}_0 \sim N \left(\beta_0, \sigma^2 \frac{\frac{1}{n} \sum_{i=1}^{n} x^2}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \right) \tag{20}$$

$$\hat{\beta}_1 \sim N \left(\beta_1, \sigma^2 \frac{1}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \right) \tag{21}$$

According to Mosler and Schmid, 2003, p. 299 the estimated standard deviations of the regression coefficients $\hat{\beta}_0$ and $\hat{\beta}_1$ are part of the regression model. As an estimate for the standard deviation of the regression coefficient Mosler and Schmid, 2003, p. 298 suggests:

$$\widehat{\sigma_{\hat{\beta}_0}} = \hat{\sigma}\sqrt{\frac{\frac{1}{n}\sum_{i=1}^{n} x_i^2}{ns_X^2}} \quad \text{und} \quad \widehat{\sigma_{\hat{\beta}_1}} = \hat{\sigma}\sqrt{\frac{1}{ns_X^2}} \tag{22}$$

5.2.2 Testing the results of a regression analysis

To evaluate the Regression Analysis and support the interpretation of its results the following paragraphs present analyses and discussions for (i 5.2.2) the significance of the model and (ii 5.2.2) the goodness of fit of the regression line.

To assess the goodness of fit, i.e. to determine how well the regression line approximates the data two indicators are calculated: (a) the coefficient of determination R^2 and (b) the standard error of estimate SSE. The coefficient of determination may indicate a positive or negative correlation and the strength of it. Commonly a significant correlation is assumed when it exceeds 0.6. However, this coefficient may be affected by the variances of x and y, compare Urban, 2011, p. 59 and thus its expressiveness is limited. For further validation, the standard error of estimation is used as a second indicator of the goodness of fit. The standard error of estimation measures the standard deviation of the residuals. When compared to the standard deviation of the dependent variable, it indicates how much of the data variation was explained.

Evaluating the significance of the model via F-test: This approach tests the significance of the model, i.e. whether the regression describes the data better than a random normal distribution Urban, 2011.

F-value calculation and rational: for the F-test Urban (2011) form the quotient of the shares of the "explained" regression variance and the "unexplained" error variance based on the total variance, formulated in equation 23. The authors[64] argue that the term "explained" variance is misleading. As the regression itsself does not provide explanation, a theoretical analysis needs to support that x provides an explanation, see Urban, 2011, p. 56. . Hence, the terms regression variance and error variance are used, see equations 23.
F-value:

$$F_r = \frac{\text{share of regression variance}}{\text{share of error variance}} \tag{23}$$

Why compare the quotient of the variances to an F-distribution? An F-distribution is composed of the quotient of two chi^2 distribution. One chi^2 distribution represents the sum of squares of randomly distributed values. Comparing this to variances means, if the values are randomly distributed, then a) their variances are chi^2 distributed and b) the quotient of these variances are f-distributed. If this

[64] Regressionsanalyse: Theorie, Technik und Anwendung 2011, ISBN 978-3-531-17345-0

statement holds true for the equation 23, then the regression model does not describe the values better than a random distribution. If the test can be rejected, the regression explains the values and the correlation between the variables is significant.

When can the test be rejected? To answer this question, the fisher probability distribution function pdf is analysed, which shows the number of f-distributions for each F-value (x). The pdf shows many fisher distribution for low F-values. In the cumulated distribution function (cdf) below one reads that 95% of the fisher distributions have an f-value of 4.85 or lower. Consequently, if the F-value is bigger than that, there is a 95% chance that the distribution is not an f-distribution. In that case the hypothesis that our distribution is an f-distribution will be rejected accepting an error of 5%.

Note that the confidence interval and the illustrated fisher distribution in figure 10 are based on the parameters d_1,d_2 for the analysis on hand. These parameters, $d_1 = m-1$ and $d_2 = N-m$ integrate the number of dimensions or regression coefficients $m = 2$ and the number of samples $N = 76$ into the fisher distribution.

$$m\text{- number of regression coefficients} = \text{number of dimensions (2)} \tag{24}$$

$$N\text{- number of samples (76)} \tag{25}$$

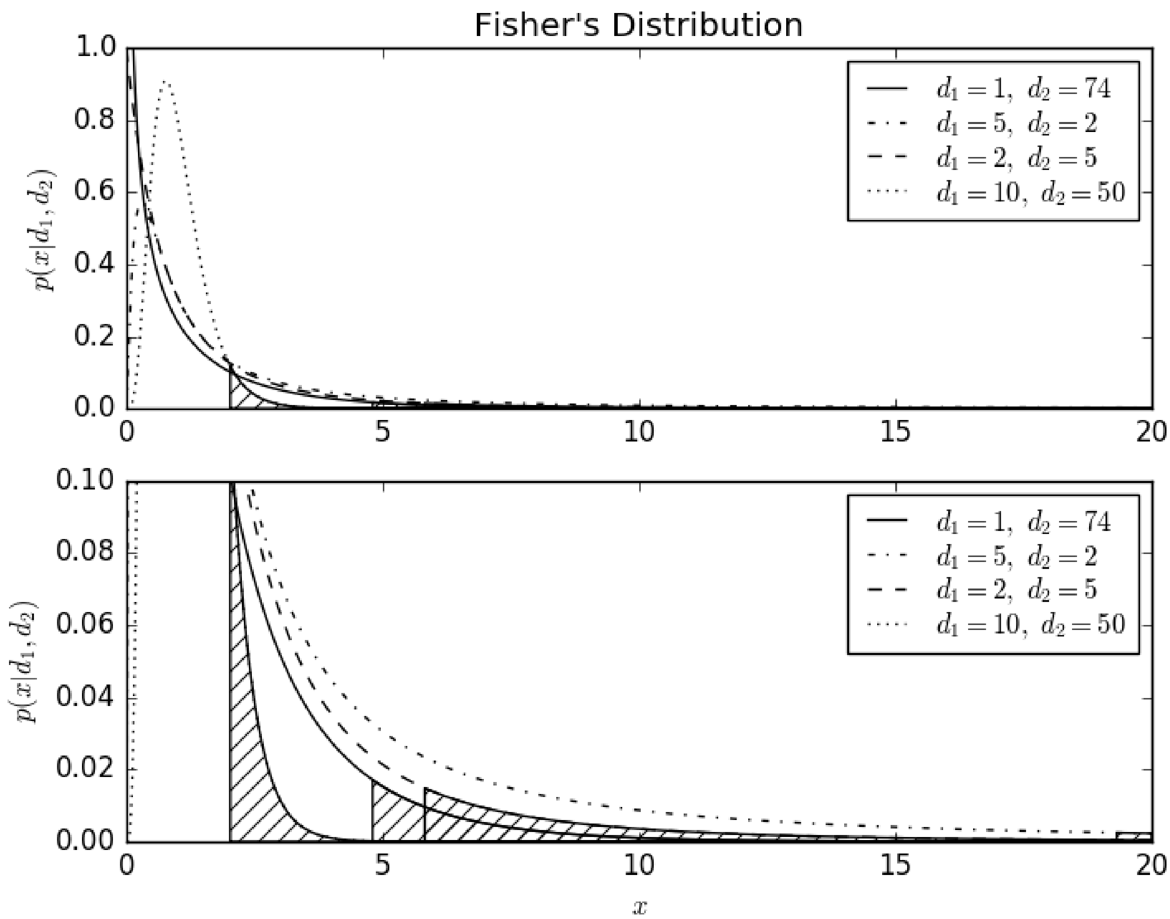


Figure 10: Fisher probability density function (pdf) and cumulated density function (cdf) for $d_1 = 1, d_2 = 74$

What are the components of the f-value? As the F-value is composed of the fraction of two shares with the same base, i.e. the total variance of the sample, this base can be eliminated. As a result, the f-value is the fraction of the regression variance and the error or residuals variance. F-value:

$$F_r = \frac{\text{regression variance}}{\text{error variance}} \tag{26}$$

In equation 26 the regression variance is the sums of squares (SoS) of the values approximated by the regression model. In detail, it represents the sum of the squared distances of the estimated values on the regression line to the mean, see Urban (2011, p. 57):

$$\sigma_Y^2 = \frac{1}{n}\sum_{i=1}^{n}(\hat{Y}_i - \bar{Y})^2 = SoS_{reg} \tag{27}$$

The error variance in the denominator of the formula describes the variation in the residual and equals the squared standard error of estimation (Urban, 2011, p. 58):

$$\sigma^2 = \frac{\sum_{i=1}^{n}(\hat{Y}_i - \bar{Y})^2}{N-2} = \frac{SoS_{err}}{N-2} \tag{28}$$

This formula for the error variance is congruent with Mosler and Schmid, 2011 calling it residual variance, where U_i are the residuals $\hat{Y}_i - \bar{Y})^2$, and providing the following estimate:

$$\sigma^2 = \frac{1}{n-2}\sum_{i=1}^{n}(U_i^2) \tag{29}$$

$$\tag{30}$$

Calculating the f-value thus follows the equation:

$$F_r = \frac{\text{share of regression variance}}{\text{share of error variance}} \tag{31}$$

$$= \frac{\frac{SAQ_R}{SAQ_B}}{\frac{SAQ_F}{SAQ_B}\frac{1}{N-2}} = \frac{SAQ_R}{SAQ_F}(N-2) \tag{32}$$

Alternatively, Urban (2011, p. 155) provide the equation based on the coefficient of determination. This coefficient can be expressed as the fraction of the regression variance and the total or observed variance, see Urban (2011, p. 57) . It may also be calculated using 1 - fraction of error variance and total variance, see equation 35.

$$R^2 = \frac{\text{regression variance}}{\text{observed variance}} \qquad = 1 - \frac{\text{error variance}}{\text{observed variance}} \tag{33}$$

$$R^2 = \frac{SAQ_R}{SAQ_B} \qquad = 1 - \frac{SAQ_F}{SAQ_B} \tag{34}$$

$$R^2 = \frac{\frac{1}{n}\sum_{i=1}^{n}(\hat{Y}_i - \bar{Y})^2}{\frac{1}{n}\sum_{i=1}^{n}(Y_i - \bar{Y})^2} \qquad = 1 - \frac{\frac{1}{n}\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{\frac{1}{n}\sum_{i=1}^{n}(Y_i - \bar{Y})^2} \tag{35}$$

Consequently, the detailed formula for the f-value is depicted in equation 37.

$$= \frac{R^2/(m-1)}{(1-R^2)/(N-m)} \tag{36}$$

$$= \frac{\frac{SAQ_R}{SAQ_B}/(m-1)}{\left(1-\left(1-\frac{SAQ_F}{SAQ_B}\right)\right)/(N-m)} \qquad = \frac{\frac{\sum_{i=1}^{n}(\hat{Y}_i-\bar{Y})^2}{\sum_{i=1}^{n}(Y_i-\bar{Y})^2}/(m-1)}{\left(1-\left(1-\frac{\sum_{i=1}^{n}(Y_i-\hat{Y}_i)^2}{\sum_{i=1}^{n}(Y_i-\bar{Y})^2}\right)\right)/(N-m)} \tag{37}$$

5.2.3 Ergodicity

In statistics, the term describes a random process for which the time average of one sequence of events is the same as the ensemble average. In other words, for a Markov chain, as one increases the steps, there exists a positive probability measure at step n that is independent of the probability distribution at initial step 0, cf. Feller (1971, p. 271).

The correlation of use intensity (density) and population growth is shown for different cities with a variation of population growth. Then the correlation is applied to each city with a population growing over time. . This approach assumes that cities take on the same states over time. This is not completely possible, as in different times and cities the policies concerning new buildings and building land vary, the research evolves and introduces new variants of buildings and input for spacial planning, the building stocks of the cities vary and may be more or less suitable to adjust to new people (spacial apartment design). However, this approach will be used, as the main facts stand: (i) more people need more space (ii) delay in providing new living space and (iii) construction limitations.

Based on the method described in the previous section, the following paragraphs will describe how the growth factors are designed and assumed and why.

5.3.1 Correlation of population growth and space use intensity

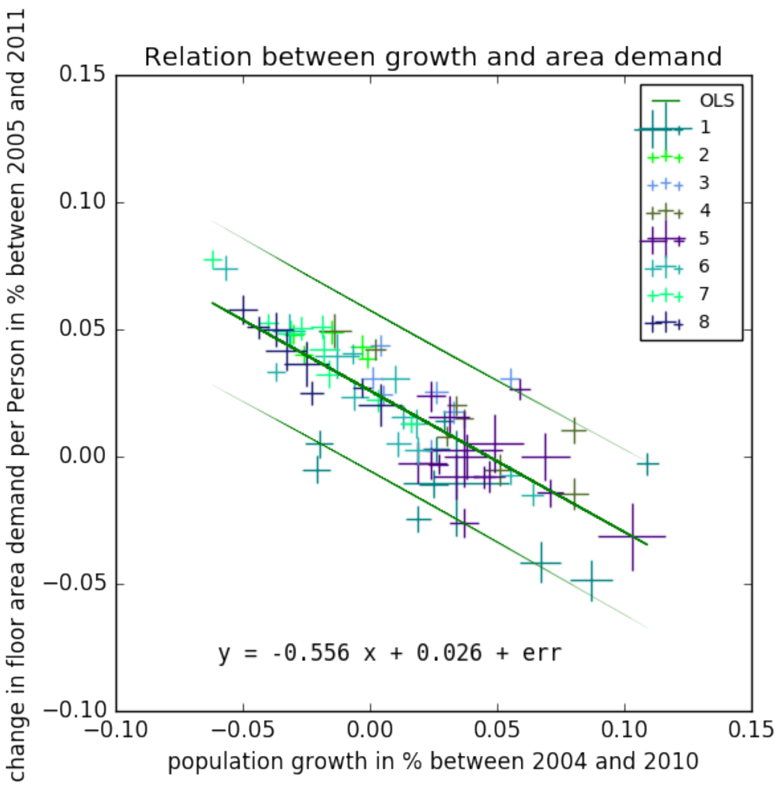


Figure 11: correlation of population growth and space use intensity, own analysis based on wegweiser-kommune.de, 2012

The scatter plot indicates negative correlation and shows the cities coloured by cluster and with the „+“ marker revealing their size. Basis for this chart are data population data from the Federal office of Statistics, see table 23 in the Appendix on page X. The data for the development of per capita floor area demand and population growth is provided by Bertelsmann Stiftung, 2014. Based on he distribution of the data points in the scatter-plot a linear function appears to be suitable to describe the correlation amongst the variables. Furthermore, the data appear to be negatively correlated, i.e. with growing population the per person floor area demand declines. Finally, no noticeable, extreme outliers are visible.

The regression coefficients support a significant a negative correlation. This model is now applied to the data collected for population growth and floor area demand per person. The population growth between 2005 and 2011 for each city forms the regressor, i.e. the independent, controlled X Variable. Accordingly, the development of the per capita floor area demand for each city forms the measured, dependent Y Variable. The calculation was conducted with the statsmodels.api an ipython module installed on the anaconda framework.

The data for the regression analysis stem from the micro census Statistisches Bundesamt, 2011a, 2014 and from the demographical study (Bertelsmann Stiftung, 2014). The regression coefficients and their properties result from the formulas presented in 5.2.1:

parameter	value	std err	t	P>|t|	95% Conf.Int.
$\hat{\beta}_0$	0.0259	0.002	13.548	0.000	0.022 0.030
$\hat{\beta}_1$	-0.5556	0.047	-11.730	0.000	-0.650 -0.461

Table 16: OLS Regression Results

R-squared and standard error of estimate prove the goodness of fit: The coefficient of determination may indicate a positive or negative correlation and the strength of it. Commonly a significant correlation is assumed when it exceeds 0.6. However, this coefficient may be affected by the variances of x and y, compare Urban (2011, p. 59). For further validation, the standard error of estimation is used as a second indicator of the goodness of fit. The standard error of estimation measures the standard deviation of the residuals. When compared to the standard deviation of the dependent variable, it indicates how much of the data variation was explained.

$$R^2 = 0.650 \tag{38}$$

$$SSE/\sigma_y = 0.599 \tag{39}$$

The coefficient of determination takes on a value of 0.65 and thus indicates a significant correlation according to Urban, 2011. The standard error of estimation compared takes on 60% of the standard deviation of the dependent variable. This reduction in variance of 40% indicates that the regression line suitably fits the data. The regression model is thus:

$$Y_i \sim N(0.0259 + -0.5556\, x_i \quad , \quad \sigma^2 = 0.650) \tag{40}$$

The f-test supports the significance of the identified regression model. Through the f-test the explanatory strength of the regression will now be compared to a random distribution. If the hypothesis of the f-test can be rejected, the regression explains the values and the correlation between the variables is significant. The hypothesis can be rejected, if the f-value lies above 4.85. Then the test value is assumed to be not f-distributed and to lie within the grey area of the following. As there are another 5% of the f-distributions within that interval, one can be 95% sure that the test value is not f-distributed. However, to reject the hypothesis this uncertainty can be accepted.

Figure 12 shows that the confidence interval starts at 4.85. As the calculated f-value is 137 it not only exceeds the confidence limit for 95% but also the one for 99%. Hence, with 99% certainty one can assume that the regression model is suitable.

$$\text{f-value} = 137.0 \tag{41}$$

5.3.2 Distribution of vacancy across building types

As opposed to the construction in growing cites, buildings become vacant when population decreases in shrinking cities. Since the unused living space is assumed not to be heated, the population reduction

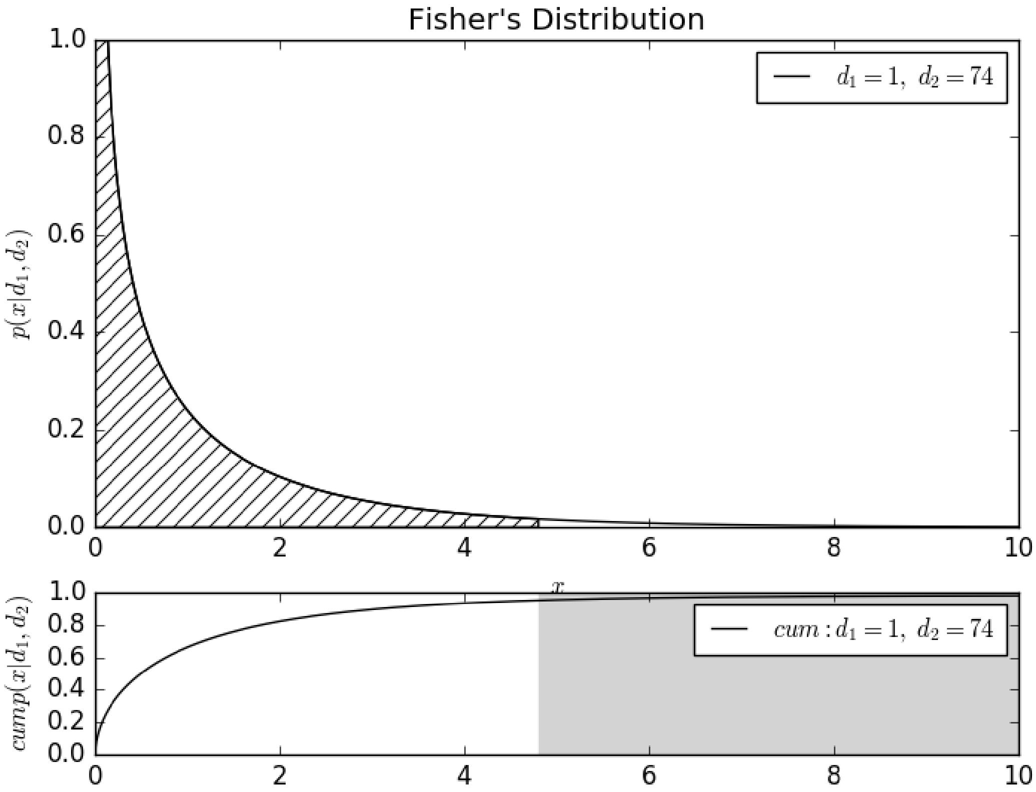


Figure 12: Fisher probability density function (pdf) and cumulated density function (cdf) for $d_1 = 1, d_2 = 74$

triggers a decrease in energy demand. Which building ages and geometries will be vacant and which will be continued to be used, may have an influence on energy demand.

According to Linke (2013) structural vacancy[65] in shrinking rural regions occurs to buildings that are rather unattractive with respect to their layout, energy consumption, location, i.e at through roads, or technical equipment, i.e. heating system. Not without further assessment can the localization of vacancy within the historic center be conveyed from the observed villages to shrinking cities. Here, the historic city center is often an attractive location as transport, social and economic infrastructure are usually available.

Banse and Effenberger (2006, p. 16) and Braun, Heising, and Schwede (2014, p. 7) found that more than 80% of vacant living units are within multifamily buildings. Apart from that, the vacancy is also differently distributed over construction periods. According to Simon-Philipp and Hopfner (2013, (p. 34)) multi-family buildings built between 1949 and 1978 hold a predominant share of 27% of Germanies vacancy. A reduction of vacancy in older multi-family buildings (construction before 1918) and increased vacancy in medium-aged buildings was observed, in eastern Germany comparing 1998 and 2002, see Banse and Effenberger (2006, p. 16). Based on that, the vacant living space for the big German cities was distributed across multi-family buildings older than 25 years and younger than 100 years.

[65] Structural vacancy includes buildings and living units that are available on the market. It excludes cases, where owners decide to leave the building vacant or the ownership is unclear.

5.4 Interpretation, discussion and use of the growth factors

The determined functional correlation comprises two overlaying effects: the change in use intensity driven by the migration processes and the trend of decreasing household sizes, compare Deschermeier and Henger, 2015, (p. 23). Both affect floor area demand per person.

Firstly, the increased rental and real estate prices are one reason for people to demand less floor area in growing cities. The floor area demand of the new population especially in city centres drives prices, which may convince people to choose a shared apartment. The lack of small affordable apartments causes this reaction especially when younger people move to growing cities. Residing inhabitants on the other hand are not immediately affected as the rent increase of an existing contract often lags behind the market prices for new rentals. For the inhabiting population to settle for less floor area, the rent saving also needs to cover the cost of moving.

On the other hand, the increased floor area demand in shrinking cities occurs when mainly younger people leave their parental home and medium aged people with or without family make a work-related move. In this case, the remaining population does not move into bigger living units and does not take part in the market. Hence, falling prices may be a consequence of the shrinkage but likely do not impact the increase in floor area demand.

Secondly, the overall change in per capita floor area demand also reflects decreasing household sizes. The declining use intensity in moderately growing cities is an indicator for the general trend for more per capita floor area related to the tendency towards decreasing household sizes. German national statistics project the increase of life expectancy, job mobility, separate households for one family and low birth rate causing the household sizes to decrease within the 2030 horizon.[66]

5.4.1 Limitations of the correlation analysis

The assumed linear correlation is only valid within limits. The lower limit of living space per person is determined by the minimal living space per person or the maximum price a person is willing to pay for additional living space. That maximum price is dependent on each person's income situation and alternative expenditures. When this limit is reached the price does not react to the growing population as much. In this case, the population will move out of the city and accept increased transfer cost and time. In case a city shrinks there is also a limit to the price decay. It is determined by the landlord's opportunity cost or missing benefits. Is the rent too low, the landlord may not take up the trouble and transaction cost of letting. For the tenant each additional m^2 of floor area possesses a lower additional value. This additional value needs to weigh-off the trouble of moving and possibly additional commute to the alternative bigger living unit.

The impact of city size and growth restrictions is excluded within the analysis of population growth and floor area demand. Although the size of a city and urban and land use planning restriction may impact

[66] Statistisches Bundesamt, 2011b, p. 30.

how a city is growing further and how much and which floor area is demanded; these factors are not considered within the scope of this analysis and may be subject in future research.

Uniform growth is assumed. The population change that has been projected within Bertelsmann Stiftung, 2014 between 2011 and 2030 may affect a city gradually or in bigger chunks at a time. The aspect of growth speed has been disregarded within this analysis due to lack of empirical evidence, but it offers a wide arena for future research.

Use intensity is constant for all building types in all city areas. The assumption that a square meter in a suburban single family building is used as intensely as a multi-family building within or close to the city center needed to be made as there are no consistent data on population, age and income distribution in different areas or buildings types for all cities. However, the suggested cluster analysis in chapter 3 may be a basis to perform such research.

5.4.2 Assumption derived for the impact assessment of gowth

Use intensity (m^2/cap): The living space per person is adjusted based on how much the city grows or shrinks, as suggested by the results of Bräuninger and Otto, 2006, p. 537, see section 5.3. Figure 11 on page 49 shows that a correlation between population growth and living space per capita can be approximated through linear regression, using the data from Bertelsmann Stiftung, 2014. The linear correlation with the determined parameters is used as an assumption for the further assessment. As a result, the per capita living space demand will decrease with population growth according to equation 40. This assumption is the basis for the evaluation of the effect of growth on energy savings. The population change directly leads to an increased or diminished demand for residential units. Therefore in growing cities new buildings are assumed to be built to fulfil that demand. In our analysis the distribution of new buildings equals the distribution of the latest building period (2011) in the typology data (Diefenbach and Loga, 2011). That means, the new building trend is assumed to continue, which reflects the trend suggested by Banse and Effenberger, 2006, p. 29. However, it could be argued that cities may become denser and may not be able to grow in the same way they grew in the past.

These results may be argued as the data provides a comparison of different cities and not a time line for one city, see ergodicity discussion on page 48. Moreover, the coefficient of determination of 0,59 is moderate. However, both data disadvantages seem acceptable considering that existing research, like Monkkonen, Wong, and Begley, 2012 provides empirical evidence in favour of the correlation. Therefore, the current and local data for German cities was used to amend the growth of living space demanded. The linear approximation of this correlation is, however, only valid within boundaries, since living space use is cost driven and utility costs increase with space as explained in Spars, 2006, p. 29. The resulting per-person-living spaces for the cluster cities are within these boundaries of 45 m^2/cap.

Vacancy distribution: To assess the effect of a predominant vacancy in multifamily buildings older than 25 years and younger than 100 years was assumed for the scenarios GROW and GRIN.

Three different demographic developments are distinguished to assess the impact of demographic change, i.e. here the growth and shrinkage of a city.

Firstly, the CONST development simply ignores the population change and the related new construction and vacancy. In a projection of the building stock and its energy demand until 2030, only the energy performance of the buildings will change. This change is driven by energy retrofit of the building envelope and improvements of the heating system.

Secondly, the GROW development includes the population change projected by Bertelsmann Stiftung, 2014, i.e. net population migration, but assumes a constant living space per person ratio. Within this development the used building stock grows and shrinks according to population migration.

Thirdly, the GRIN development factors in the change in use intensity, i.e. in living space per person. This is a results from the assessment in chapter 5.3 where it is shown that a shrinking city's population occupies more living space whereas strongly growing cities tend to compress. In either direction, the change in floor area is not as strong as the change in population. With the assumption of a constant floor area heating behaviour, the energy demand behaves similarly.

6.1 Quantification for Germany

Table 17 shows the change in population and floor area for all of the demographic developments in 2030 compared to the base year 2010. This table is does not distinguish the policy pathways, as they do not affect population change, floor area and use intensity.

6.1.1 Change in population and floor area

Bertelsmann Stiftung, 2014 foresees a trend towards urbanization (Geppert and Gornig, 2010) causing the population in Germany's big cities to grow by 1.48% [1] in total, see table 17. However, this moderate average population growth splits up into a growth rate of almost 5.83% [6] for the 45% [4] growing cities while 55% [5] of cities shrink at an average of 6.49% [7].

The population growth and shrinkage has different effects on the floor area used per person - the use intensity. The effect on per capita floor area can be assessed by applying the functional correlation, which was determined through a regression analysis in chapter 5.4. This functional correlation covers two overlaying effects. Firstly, the total population growth induces an increased total floor area demand: more people, higher area demand. This effect is strengthened by the trend of decreased household sizes and the consequential increase of the average floor area demand per person. Secondly, the increased rental and real estate prices cause people to settle for less floor area demand in growing cities. As a result, the population requires 0.76 m^2 [10] fewer per capita floor area in strongly growing big German cities, which applies to 14% [8] of the big cities. Within the 86% [9] shrinking cities, the per capita floor area increases. On average, a person here requires 1.48 m^2 [11] more floor area in 2030 than in 2010.

The total change in floor area results from overlaying the population growth and shrinkage with the induced change in the per capita floor area demand. This calculation shows an increase in 67% [12] of big German cities by an average of 4.34% [14] and a decrease in 33% [13] of the cities by 1.63% [15] of the total floor area.

Table 17: scenario results: population migration and induced change in floor area in Germany's big cities

Scenario	city count	city share		population change		floor area change GROW		floor area change GRIN		use intensity change in m^2/cap GRIN	
				1.48%	[1]	1.32%	[2]	2.95%	[3]		
population change perspective											
growing cities	34	45%	[4]	5.83%	[6]	5.75%		5.04%		-0.28	
shrinking cities	42	55%	[5]	-6.49%	[7]	-6.51%		-0.75%		2.41	
use intensity (m^2/cap) perspective											
cities with increasing floor area use	11	14%	[8]	8.21%		8.19%		6.02%		-0.76	[10]
cities with decreasing floor area use	65	86%	[9]	-2.44%		-2.48%		1.25%		1.48	[11]
floor area perspective											
cities with increasing floor area	51	67%	[12]	4.31%		4.20%		4.34%	[14]	0.01	
cities with decreasing floor area	25	33%	[13]	-8.10%		-8.14%		-1.63%	[15]	2.75	

6.1.2 Energy demand and savings

To assess the impact on energy demand and energy savings the demographic developments are combined with the three policy pathways: BAU, CP80 and CP95, as described in chapter 7.

Surprisingly, the effect of an overall growing population on total energy demand is not linear. As the population in total grows by 1.48%, see table 17, the energy demand decreases in the GROW scenario by 0.58% [1] and increases in the GRIN scenario by 1.14% [2] compared to the constant population reference CONST.

As a starting point for the explanation, the energy demand of the analysed cities sums up to 160.7 TWh [3] in 2010. With the assumption of a constant population, the energy measures within buildings within the CP80 scenario reduce the energy demand to 105.8 TWh [4] in 2030. If then purely the expected population change in the different cities is included the energy demand shrinks further to 105.2 TWh [4].

The reason for this non-intuitive result is the changing distribution of the population across building ages caused by migration. While the population and the floor area grow in total, in detail, single cities grow while others shrink. Within the latter, existing and possibly old buildings with a low energy performance are now no longer used. Their former inhabitants now increase the energy demand elsewhere, likely in new building with a lower energy demand. This effect induces an increase of the energy savings by 1.12%[67]. As opposed to the increased energy savings within the GROW scenario, slightly lower energy savings are realised in the GRIN scenario. It considers the growth induced change of the floor area demanded per capita, which is overall positive due to the national trend in decreasing household sizes. Subsequently, the energy demand slightly increases to 107.0 TWh [6].[68]

[67] The percent energy saving increase results from the ratio of the GROW scenario savings (105.2 TWh - 160.7 TWh) compared to the CONST population savings (105.8 TWh - 160.7 TWh)

[68] Within the calculation a possible change in heating behaviour with higher floor area is not considered. If empirical research on the behavioural change of heating with growing or shrinking floor area demand, it would add more detail

Secondly, the migration causes new buildings with better energy performance to be built in growing cities and leaves existing buildings with a lower energy performance vacant in shrinking cities. As a result of this replacement construction effect, the average energy demand per m^2.

Table 18: Scenario Results for all German big cities

policy pathway demography development		BAU 2010		CP80 CONST	compared to CP80 CONST	CP80 GROW	compared to CP80 CONST	CP80 GRIN	
population		24,616,943		24,616,943	<	24,980,051	<	24,980,051	
floor area	m^2	44,160,559		944,160,559	<	956,651,624	<	972,017,620	
energy demand	GWh	160,675	[16]	105,825	-0.58% [17]	105,208	+1.14% [18]	107,027	[19]
energy investment, thereof ...	10^3 Euro			363,338,234	-0.37% [20]	361,984,614	+1.54% [21]	368,923,453	
... in existing buildings	10^3 Euro			361,825,057	-2.46% [22]	352,923,587	-0.29% [23]	360,784,724	
... in new buildings	10^3 Euro			1,513,177	>	9,061,027	GROW -10.2 [24]	8,138,729	[25]
energy demand per m^2			112	-1.88% [26]	110	>	110		
change in invest per m^2	%					-1.67	[27]	-1.37	[28]

6.1.3 Investments

The impact of growth and shrinkage in German cities on the investment sum [69] for energy saving measures combines two overlaying effects for existing buildings and new buildings [70] .

The growing floor area demand, see table 17 [2], causes an increased new construction and thus larger investments for energy measures in new buildings to 8.13 million Euros , see table 18 [25]. The observed decrease in per capita floor area in growing cities[71] avoids an additional 10.2% [24] increase in energy investment, that is included in the GROW scenario.

The investment in existing buildings decreases by -0.29% [23], see table 18, although the overall population increases by -1.48%, see table 17 [1]. Background of this development is the reduced renovation activity in shrinking cities. A comparison of the CONST and the GROW scenario additionally reveals that without use intensity change (floor area per person increase in shrinking cities) the investment for energy measures in existing buildings would end up about -2.46% [22] lower. This rebound indicates that the additional floor area uptake in shrinking cities and moderately growing cities outweighs the squeeze up in strongly growing cities.

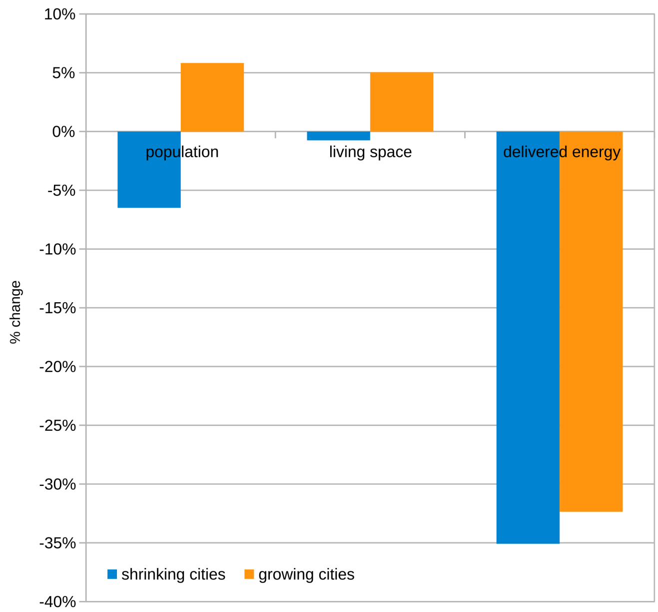
All in all, due to the change in population (GRIN) the energy investment increases by 1.54% [21], see table 18, while the floor area increases by 2.95% [3], see table 17. The dampening effect on investments can be explained as the investment per m^2 decreases by -1.37 [28].

to this analysis. However, existing studies have shown that heating behaviour significantly varies amongst households Rohde et al., 2012, p. 22

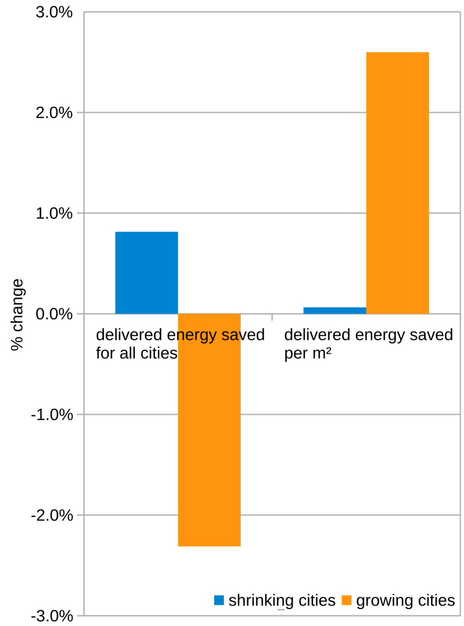
69 The magnitude of the total investment of about 363 billion Euros [20] in the period between 2011 and 2030 is equivalent to an annual investment of 19 billion Euro, which is in the range between 10 and 30 billion Euro, projected by Prognos AG and Öko-Institut e.V., 2009, p. 24.

70 The modelled new construction incurs at least those energy investments that fulfil minimum requirements by the EnEV. This is assumption can be controversially discussed as in reality there is no effective control on the compliance to the EnEV and experience and interviews show indicate a significant deviation in real investment behaviour.

71 See chapter 5.3.



(a) population growth and its effect on living space and delivered energy savings



(b) Extracted impact of demographic change on energy and retrofit investment

Figure 13: Impact of demographic change shown as a comparison of the scenarios CP80 CONST and CP80 GRIN

The separate display of key parameters for growing and shrinking cities reveals the components of impact of demographic change. The population development translates into livings space on a diminished scale for both growing and shrinking cities. That means, the living space reduction in shrinking cities amounts to 11.6% of the population reduction, whilst the living space in growing cities amounts to 87% of the population growth. With respect to energy demand this is a positive indication for the energy saving and climate protection due to the high dependency of energy demand on living space.

The delivered energy change over time (13 (a) on the right) shows the effect of the renovation path CP80 with energy savings of more than 30%. It also shows that all shrinking cities save 8% more energy than growing cites between 2010 and 2030, due to net population emigration. When comparing the delivered energy savings to a scenario without demographic change (CONST) the impact of the policy path is eliminated and the impact of the demographic change becomes more obvious. Such comparison is conducted in Figure 13 (b), which shows negative delivered energy savings within growing cities on the left, which means that the energy saving measures do not compensate the population growth.

The delivered energy savings per m^2 indicate the energetic quality of the building stock and reacts positively to demographic change for both shrinking and growing cities. The details of this effect are further explored within a drill down by clusters in section 6.2.2. Finally, the retrofit investment analysis demonstrates that despite increase of investment[72] within growing cities energy saving measures cannot make up for the population growth and the delivered energy savings are negative. On the other hand, the

[72] shown as a negative investment saving

population decrease within in shrinking cities lets the delivered energy shrink despite a large reduction in retrofit investment. Details on demographic change components effects on investment are presented on page 61) .

6.2.1 Energy savings within growing and shrinking cities of different clusters

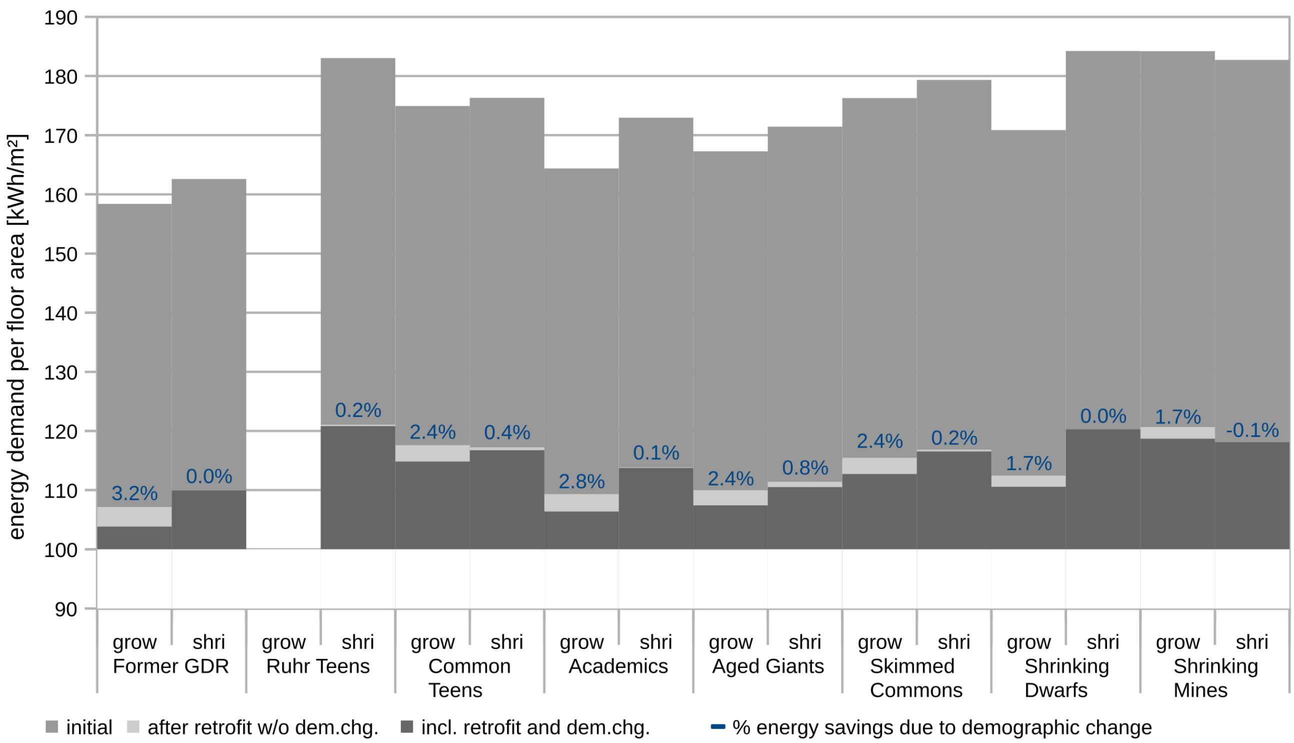


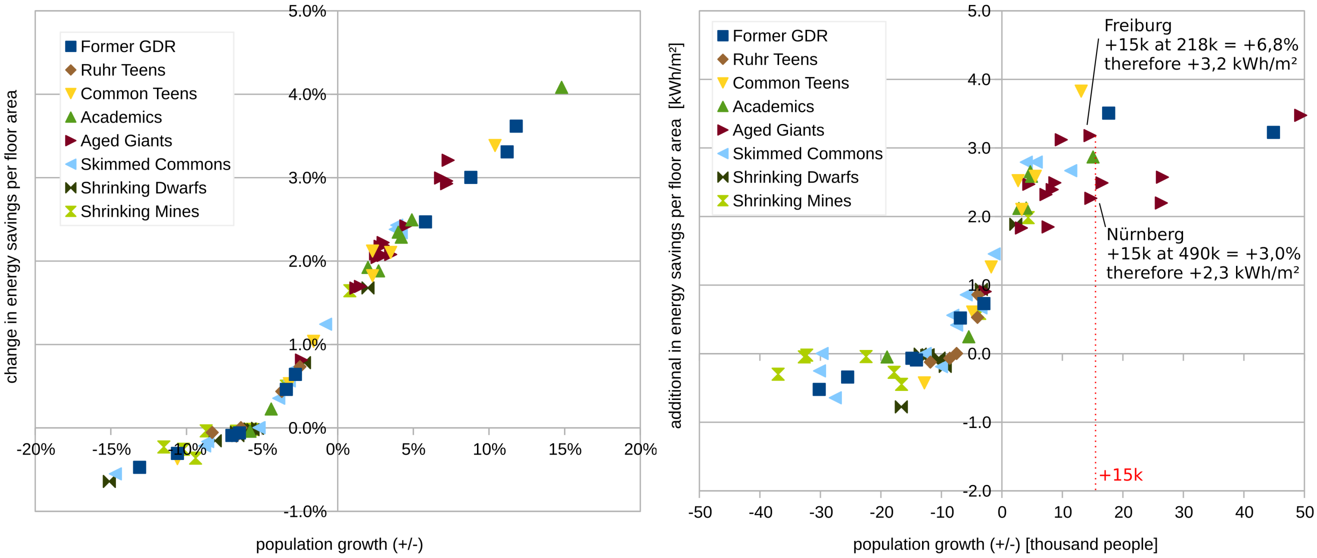
Figure 14: Reduction of energy demand per floor area through energy retrofit and demographic change (pop.+/-)

Despite their increasing population, growing cities gain in energy savings. Figure 14 shows the energy demand per floor area averaged by cluster (a) in 2010 as a large bar in medium gray, (b) in 2030 after retrofit but assuming a constant population (GROW) as a light bar, and (c) in 2030 after retrofit but including demographic change: population growth and use intensification. Surprisingly the growing cities of each cluster on average have more energy savings with demographic change. That means the population growth does not increase but reduce energy demand. Therefore, the effect of use intensity increase overlays the population growth on a cluster average.

6.2.2 Impact on floor area specific energy savings

Floor area specific energy demand in figure 15 shows a positive correlation to population growth (+/-) and an impact of demographic change. This impact is quantified as the difference between the scenario CP80 GRIN, which includes demographic change, and CP80 CONST, which excludes it.[73] The positive correlation suggests that the more a city grows, the lower the energy demand per m^2 in this city. This correlation can be accredited to the increasing share of new buildings that are constructed to

[73] Both of these scenarios contain the same energy measures for existing buildings for the policy pathway CP80, which will consequently not contribute to this change.



(a) percentage change (b) absolute change

Figure 15: Energy savings per m^2 impacted by demographic change, therefore comparing CP80 scenarios GRIN and CONST

accommodate the growing population. On the other hand, energy savings per m^2 decrease proportionally to the population reduction within shrinking cities until they turn into additional energy demand for population growth of -5% and below.

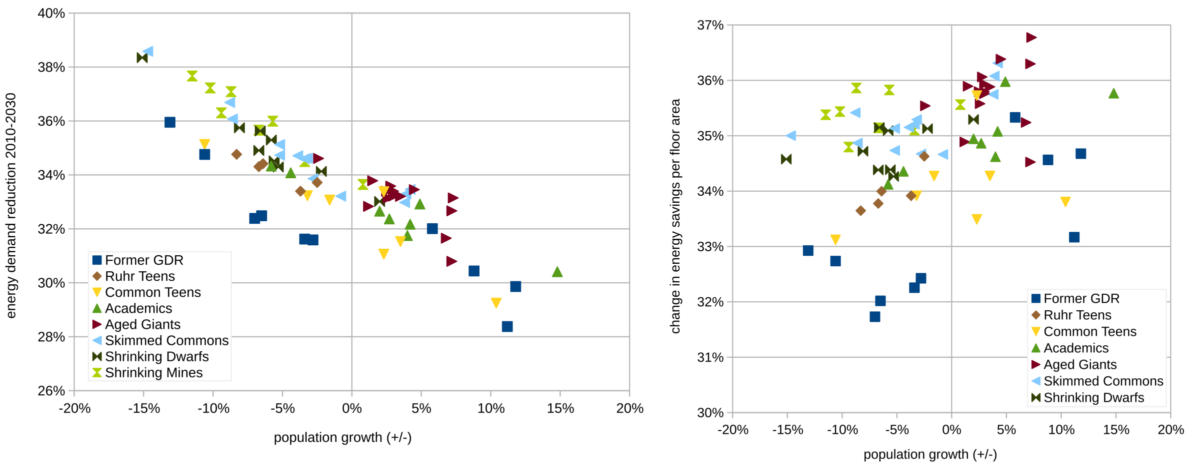
The dampened slope for negative savings accelerates energy savings when further urbanization is likely. The distribution of cities suggests that the energy losses in shrinking cities are lower than the energy savings in growing cities. The slope of an approximation of the plotted results is lower within the left section, where the energy savings become increasingly negative compared to the right section, where energy savings increase with population growth. Translating into a migration from a shrinking city into a growing city, that if a shrinking city looses 10% population and a same size city gains these 10%, more energy is saved than lost per m^2.

If cities are not the same size though, as the right side of figure 15 shows, the absolute saving per floor area depends on the current size of the city. Freiburg and Nürnberg, for example, are projected to both have a population gain of 15 thousand people. However the average energy savings per square meter are at 3.2 kWh/m^2 larger in Freiburg than in Nürnberg saving an average 2.3 kWh/m^2. As a result, this nexus cannot simply be transferred to different size cities, especially when in the urbanization process the shrinking cities are smaller than the growing cities. These three distinguished inclines result from an overlay of the buildings stock expansion with new buildings.

In detail, this means that the living space demand of the increasing population is partly fulfilled by new buildings and partly by an increased use of existing living space, i.e. in shared apartments. The increased share of new buildings lead to a decreased energy demand per m^2 in the average building stock depicted on the y-axis. In strongly shrinking cities the use intensity change increases the floor area demand which is partly covered by freed buildings due to shrinkage. For example, parents remain in their living unit although children move out. The more the cities shrink, however, the more living units become vacant.

This applies mainly within multi-family buildings, see 5.3.2, with energetically advantageous geometry, which energetically worsens the building stock composition and weakens its average energy performance. This effect is counteracted by energy saving effect of the increased share of new buildings when cities shrink up (-)5%.

6.2.3 Impact on energy savings between 2010 and 2030



(a) Energy savings until 2030(2010 vs. GRIN 2030) (b) Energy savings per m^2(2010 vs. GRIN 2030)

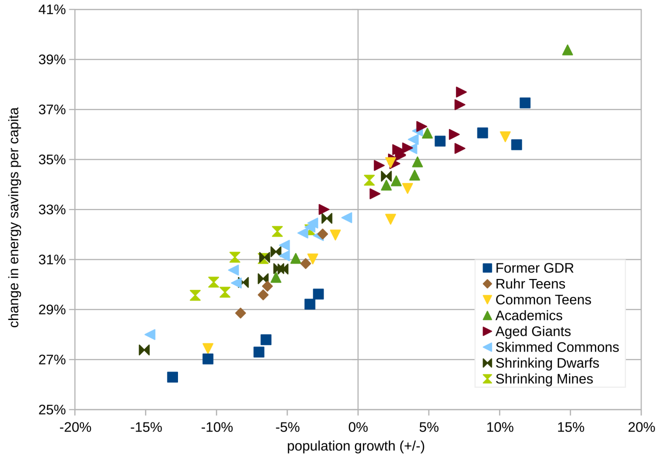
Figure 16: Impact of demographic change on energy savings for growing and shrinking cities

Despite its positive impact, demographic change does not decouple energy demand from population growth in total. This significant correlation can be observed in figure 16 (a). It evidences that the energy savings are higher within shrinking cities compared to growing cities which can be associated with the population migration. On the other hand, in figure (b), the association between the population growth and the specific energy savings per m^2 varies. Noticeably, clusters distribute distinctively which indicates an overlay with the impact of the building stock composition. To reduce that overlay the correlation is analysed again for the different clusters.

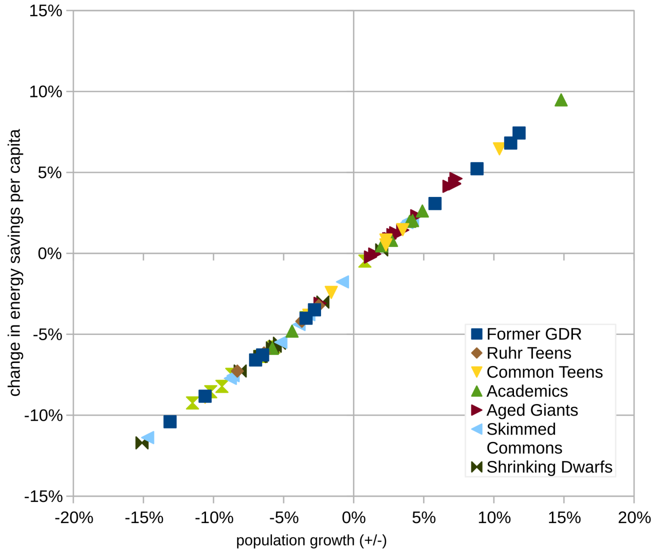
6.2.4 Impact on energy savings per person

A strong coefficient of determination of 0.98 correlates energy savings per person with growth. Part (a) of figure 17 displays that with each percentage in population growth the energy savings between 2010 and 2030 increase by 0.42%. When isolating the demographic impact in part (b) of figure 17, where GRIN development is compared to the reference CONST development with no demographic change, the correlation remains with a perfect coefficient of determination close to one.This correlation indicates that a future of increased urbanization reduces the per capita footprint of housing.
The building stock's impact is indicated by the distinct distribution of cities of several cluster. The Former GDR cluster energy savings is systematically below other clusters, while the Shrinking Mines are all saving above average per capita but also per m^2.

A migration-induced increase for growing cities and decrease for shrinking cities in all clusters displays figure 18 in the analysis of energy savings per capita by growing and shrinking cities. The varying impact of demographic change is dependent on the building stock differences and on the scale of the population growth (+/-) itself.



(a) GRIN vs. 2010



(b) GRIN vs. CONST

Figure 17: Energy savings per person impacted by demographic change

6.2.5 Investment impact for cities

The energy investment in shrinking cities is driven by retrofit, whereas the investment in growing cities is driven by energy efficiency within new buildings. At a population growth of -5%, displayed in figure 19, the composition of the total investment switches. Below this, the energy investment in strongly shrinking cities is largely driven by the retrofit activities, as the retrofit investment covers the total investment for this range. The more a city shrinks, the lower the total investment in energy retrofit. Beyond the -5% for slowly shrinking and growing cities, the energy investment in new construction takes up a higher share of the total investment.

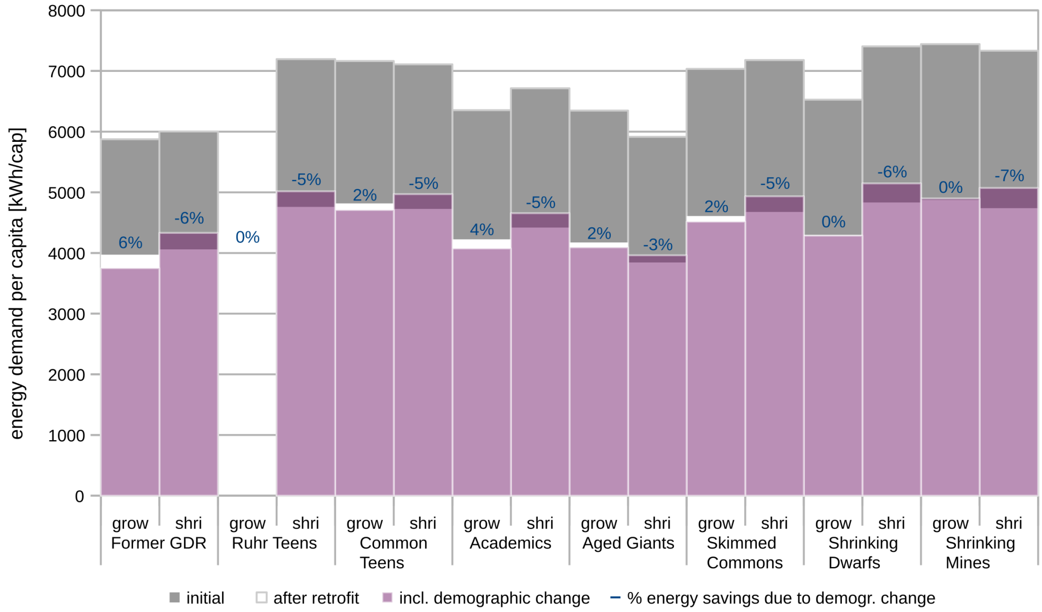


Figure 18: Development of energy demand per capita after energy retrofit and including demographic change (pop.+/-)

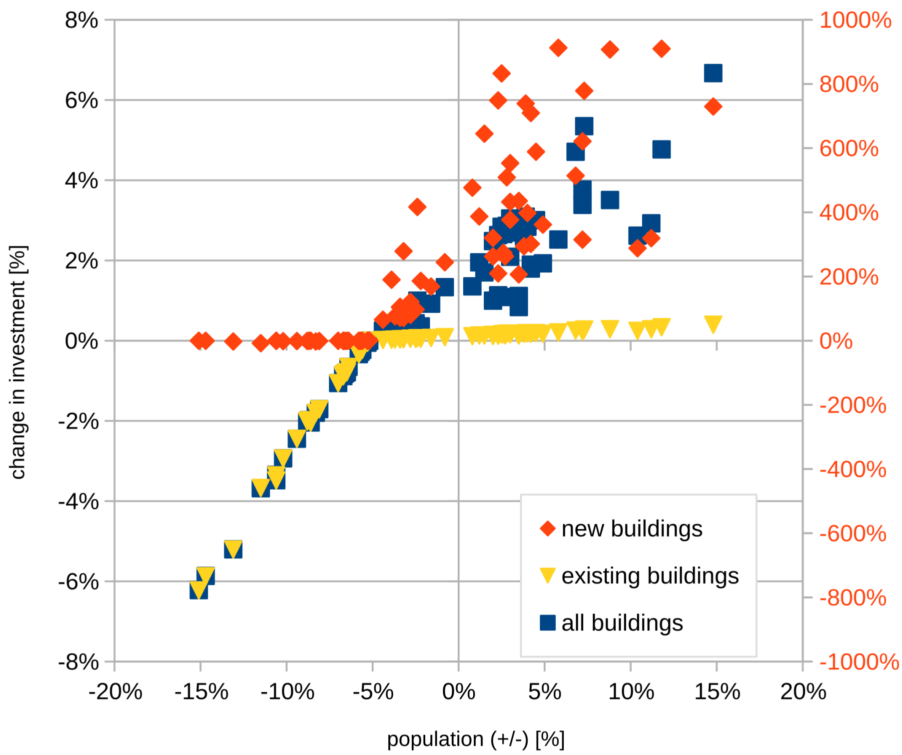


Figure 19: Impact of demographic change on energy investments for growing and shrinking cities

A trend towards bigger cities drives a replacement of old buildings in shrinking cities by more efficient new buildings in growing cities. The migration within one country induces the substitution of old buildings by new buildings accompanied by a geographical shift. In general, this effect is also transferable when population moves from rural to urban areas.

This replacement causes a drop in energy demand of -0.58% [58] and a drop in investments of -0.37As a result, this effect increases the final energy savings between 2010 and 2030 by 1.88% [12]. Simultaneously, the investment per m^2 decreases by -1.67% [15] , as the additional energetic improvement in new buildings is cheaper than in existing buildings.(see table on page 56)

Unfortunately, the gained energy savings are almost entirely reversed by the change in use intensity in shrinking cites, which takes effect in the GRIN scenario. As a result the energy demand increases at 1.14% which is still a slight improvement compared to the overall population growth of +1.48% [1](see table on page 55). The Cause for this development is that within most shrinking cities, the use intensity decreases so much that almost no vacancy arises despite the diminishing population[74]. This result however is based on the assumption of a constant energy demand per floor area. A further reduction of energy demand due to partial heating or in relation to the use intensity remains an open question for future research. Demographic change leads to an advantageous ratio between population growth and energy savings to reduce energy demand and mitigate climate change.

Within shrinking cities energy demand shrinks less than the population. This energy rebound occurs as the floor area per person increases. The following paragraphs discusses the shrinking processes to assesses this rebound. When a city shrinks there are mainly three underlying processes according to Bertelsmann Stiftung, 2014. Firstly, young people move away for jobs or educational reasons, i.e. to study or take up an apprenticeship. A large number of them move out of their parents' home. In this case, the floor area per person increases for the parents without them moving. Secondly, young families move away. As children usually have a much lower floor area per person ratio, the average floor area per person increases. Thirdly, young professionals move away. As a certain share of young professional lives in shared apartments and others do not, the effect of their emigration out of the city on floor area demand per person is not clear.

As a result, the increase in per person floor area demand seems not related to active moving processes by the people remaining in the shrinking city. On the contrary, to keep a constant per person floor area demand, these people would have to share or leave their homes and get comfortable in a new environment within the city.

Therefore, the mitigation and avoidance of the energy rebound connected to the increased heated per-person-floor area is probably easiest achieved by reducing the number of rooms heated, and by subletting rooms.

[74] Compare a floor area change of -0.75% for GRIN to a population change of -6.49% within shrinking cities, in table 17 on page 55)

Growing Cities: The total energy demand of all cities and the corresponding energy savings do not proportionally follow the upward development of the population, but grow slightly less. The reason for this is the change in per-person floor area demand caused by increased price levels and limited availability of attractive living space. For example in a growing city this means that the immigrating population increases the floor area demand (see 55) and thus the rental and real estate prices rise. As a consequence of the higher price levels, an incentive for the immigrating population is given to be satisfied with a smaller floor area.[75] The provided results evidence a correlation between floor area demand per person and population change within big cities, see page 52. Due to this effect, a city's energy savings may even increase despite its growth, as shown in an extreme but existing case on page 10. This effect, however, takes on only few percentage points off the total energy saving.

Additional factors that may influence energy demand. The results show that floor area and energy demand decreases far less than the population within shrinking cities. This energy effect may fail to materialize as projected for three reasons, which cannot be quantified within this analysis.
Firstly, the user behaviour partial heating may cause the heated area to remain constant while the total floor area increases. As partial heating behaviour is not empirically quantified, its effect can only be discussed.

Partial heating of apartments is not considered in the quantification, as research considering partial heating is not yet available. Even assumptions are discouraged as empiric evidence on the user heating behaviour shows large ranges of different behaviour in heating identical living space geometries, compare Rohde et al., 2012, p. 22 . The effect occurs as in older buildings with a high energy demand people tend to heat partly, i.e. only the living room. That is not the case in newer buildings. When people move from newer multi-family buildings located in the surroundings into the old city centre, they may want to reduce their energy bill by not heating rooms that are rarely used or have many outer walls. This effect may be caused or strengthened by an increased energy bill. However, there is yet empirical evidence needed on where people move, when a city shrinks and how their heating behaviour changes.

Secondly, a policy (re)populating the central city area is already effective within the shrinking city and i.e. the urban planning has succeeded in making the city center or parts of it attractive enough for home owners to move into this denser area or share their big family homes when children have moved out.
On the other hand, thirdly, the vacancy in a building may not affect the complete house which increases the energy demand ($\mathrm{kWh/m^2}$) as surrounding non-heated walls decrease in temperature. In this analysis it is assumed that the vacancy will progress fast within one building, as living becomes more inconvenient and expensive when neighbours move out. Such partial vacancy remains unconsidered and its impact may be subject to future research.

[75] Residing inhabitants are affected more slowly as existing contracts usually take longer to adjust to price levels.

7 Policies adjusted for growth-related demographic change

This chapter contains a suggestion on how energy policies may be adjusted for demographic change and includes an assessment of the impact of such adjustments. Therefore, policies are designed based on the starting points derived in previous chapters 5 and 6.

The quantified impact of growth and shrinkage induced demographic change in chapter 6 indicates two starting points for steering policies: (1) the use intensity increase in growing cities and (2) the use intensity decrease in shrinking cities. Firstly, as more population lives on smaller space, price levels likely rise in growing cities and renovations with higher energy savings become more profitable. With profitability being one major driver of energetic retrofit the ambition level may be increased accordingly. Secondly, policy may contain the per capita increase of heated floor area in spreading cities. If effective, that energy rebound can be avoided in shrinking cities.

Both aspects bring down the sum of investment necessary in energy efficiency. The impact of these two measures is quantified combining the existing scenarios. It is based on the assumption that they can be effectively implemented.

7.1 Approach of the assessment of growth-aligned policy

To have assess the quantified impact of such policies, the approach comprises a combination of the policy pathways of chapter 4 and the demographic developments used in chapter 6 as depicted in table 19.

Four different policy designs are formulated and foresee ambitious retrofits in densely growing cities, reflect limited retrofit in shrinking cities, and encourage limited heating in unused spaces in shrinking cities. As table 19 shows, the policy designs are generated by using the policy pathways from chapter 4.3 and the demographic developments used in chapter 6.

The suggested policy designs incorporate the adjustment of the renovation ambition to the city's demographic development, i.e. represented by its population growth[76]. This renovation ambition may be implemented in many different ways, i.e. in renovation strategies or in minimum requirements. This assessment assumes that the ambition level is effectively adjusted to the migration-related demographic development.

Table 19: Assignment of scenarios for cities with different demographic change in four policy designs

policy design	growing, condensing cities	growing, spreading cities	shrinking, spreading cities
compact efficient	GRIN CP95	GRIN CP80	GRIN BAU
dense efficient	GRIN CP95	GROW CP80	GROW BAU
compact ambitious	GRIN CP95	GRIN CP95	GRIN CP80
dense ambitious	GRIN CP95	GROW CP95	GROW CP80

[76] When a city grows or shrinks the age distribution changes as well, as mostly younger people migrate.

The most ambitious design, for example, is the "dense ambitious" scenario. It combines a CP95 retrofit pathway for growing cities with a CP80 retrofit pathway for shrinking cities. At the same time, this policy design includes those use intensity options that are best from an energy perspective: it considers shrinking floor area per person in growing cities while stopping the increase of floor area per person in relaxed growing and shrinking cities.

The labels compact and dense indicate that the rebound of the use intensity is prevented. The option compact applies this to only shrink cities, while the dense option also avoids the rebound in slowly growing cities, as shown in the analysis on use intensity on page 49. The labels efficient and ambitious mark the distribution of retrofit ambition. Within ambitious scenarios the CP80 pathway is assumed for shrinking and the CP95 pathway for growing cities. Efficient scenarios are more moderate and let shrinking cities on the current business as usual BAU pathway. Within the same scenario, slowly growing cities are retrofitted according to the CP80 pathway and growing cities in line with the CP95 pathway.

7.2 Potential impact of the developed growth-adopted policy designs

The growth-based combination of retrofit ambition levels with use intensity changes leads to a higher efficiency of energy investments.[77]

The illustration of investments over energy savings in figure 20 supports and enlarges the results shown in chapter 6.1. It presents the growth effect when comparing each GROW to the respective GRIN scenario. The market and use intensity effects of population growth induced in the GRIN scenario lead to a higher energy demand and building retrofit investments. This effect are notably smaller than the differences amongst the policy pathways BAU, CP80 and CP95. The quantification in table 20 details an increase of energy savings by about 1.7% and an increase in retrofit investment of about 2% for the policy patways CP80 and CP95.

The impact of steering policies on energy and investment is revealed by a comparison of the options dense and compact with the GRIN scenarios. The steering policies within the new policy design scenarios contain a redistribution of the retrofit investment sum as well as the floor area use intensification. A comparison of the dense efficient and compact efficient policy design scenarios with the CP80 GRIN scenario appears suitable due to their arrangement in the graph. This comparison reveals an average energy demand decrease of 2.2% and between 10.2% and 10.4% investment saving compared to the CP80 GRIN scenario.

In a comparison of investments over energy savings, depicted in figure 20 the newly created policy designs compact efficient and dense efficient show lower energy demand and lower investments than the CP80 GRIN and the CP80 GROW scenarios. The reason for that is the arc-like shape formed by the existing scenarios CP95 GRIN, CP80 GRIN, CP95 GROW, CP80 GROW, and BAU GROW (with a filled marker). This shape enables a combination of the new policy designs scenarios to reach points beneath this arc.

The arc-like shape origins from the nature of policy pathways. These pathways are energy target oriented, normative energy projections. The associated investments may not be assumed to be cost optimal for all

[77] ambition levels: BAU, CP80, CP95, are color coded and use intensity changes: GROW, GRIN, are shape coded in figure 20.

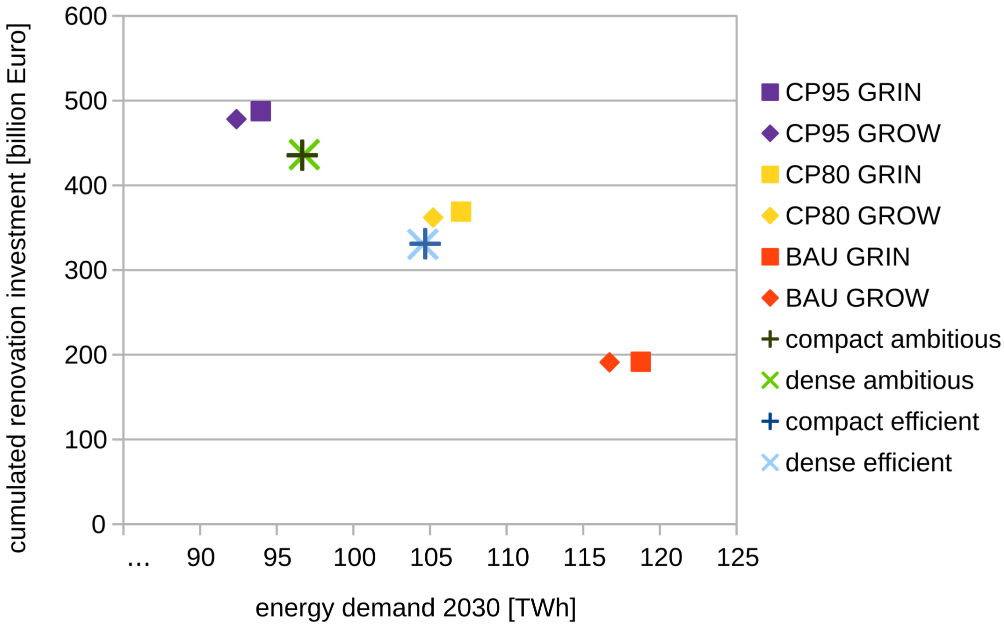


Figure 20: energy demand in 2030 and cumulated investment for steering policies and original scenarios, own calculations

three scenarios. The very ambitious CP95 policy pathways assumes non-monetary barriers to be removed, therefore energy saving measures may be available that were not available in the other scenarios. Such barriers include reluctance and constraints of home owners against air-tightness, availability of long-distance, short-distance and low temperature district heating and a building design that may today be considered unusual. Overcoming these non-monetary barriers is assumed within the very ambitious CP95 scenario leading to additional energy savings whilst the increase of investment is disproportional. The arc-like shape is the result of these assumptions and allows the combination of scenarios to enter the space below the arc.

The underlying assumption that non-monetary barriers are removed in dense growing cities but not in relaxed shrinking cities, can be explained by the following list of arguments. Density is a prerequisite for grid-based heat supply as district heating, which offer higher efficiency than single supply systems. Here the economy of scale can be applied as buildings and blocks can be jointly supplied by one system. The pure number of buildings offers a larger market for innovations under conditions that limit the technological solutions and exclude those that require near large spaces. User knowledge may spread faster which will help people in dense growing cities to adjust faster to innovative buildings, i.e. adopt a different heating and ventilation behaviour.

7.3 Interpretation and discussion of growth-based policy adjustments

Energy policy may be designed in a way that is adjusted for the demographic or population change and potentially delivers larger energy savings at lower investment. In short, such policy encourages efficient retrofit investments in buildings.

To implement such policy designs it is necessary that very ambitious renovations are conducted in growing cities with high rental and real estate prices and deliver large energy savings. Such markets offer profitability of more ambitious retrofit already today. Still, their implementation lacks behind,

Table 20: Quantified impact of growth and steering policies for the total of all big German cities, own calculations

	energy demand in 2030 (Twh)	cumulated renovation investment (billion EUR)	change in energy demand	change in renovation investment	change with respect to
CP95 GROW	92	478	0.00%	0.00%	
CP95 GRIN	94	487	1.71%	1.95%	CP95 GROW
dense ambitious	97	436	3.02%	-10.49%	CP95 GRIN
compact ambitious	97	436	2.88%	-10.65%	CP95 GRIN
CP80 GROW	105	362	0.00%	0.00%	
CP80 GRIN	107	369	1.73%	1.92%	CP80 GROW
dense efficient	105	330	-2.33%	-10.44%	CP80 GRIN
compact efficient	105	331	-2.19%	-10.26%	CP80 GRIN
BAU GROW	117	191	0.00%	0.00%	
BAU GRIN	119	192	-1.72%	-0.34%	BAU GROW

as investors strive for short term profit maximization in stable renters' markets that are in favour our landlords. Such market offer a vast floor space demand facing a limited offer, at least in preferred locations as the city centres. Living space there is demanded independent of the building's energy performance.

Due to this manifestation of the market failure, in this case, market based instruments are withdrawn as a driving force for such ambitious energetic renovations. As one option, the regulatory strengthening of such renovations remains for investor-friendly markets of growing cities.

As such renovations are very expensive, these properties become slightly less attractive for investors and the demand as one price driver on the real estate market relaxes. Prices may increase less or even decrease.

The effect on the rental market cannot be foreseen. Admittedly, there is a link between the real estate and the rental market, however, two arguments may be brought forward for their decoupling in this specific case. Firstly, the demand for living space will not increase due to the fact that buildings now have better energy performance. Secondly, the attractiveness of flats is likely more dependent on factors as location, size, shape and equipment. Especially in tight markets, it can be assumed that energy performance has an almost vanishing influence on prices, however this assumption needs empirical proof. For future research it would also be interesting to quantify the energy performance impact on prices in growing or tight and shrinking or relaxed markets.

As the market does not honour climate protection measures in buildings adequately or cost effectively, it is necessary to encourage and drive energy retrofit forward through constant political steering. Especially in growing cities with high price levels, where advantages arise on multiple levels. Firstly, the high price levels offer profitability of ambitious measures more than at low price levels. Secondly, the intense use of energy conserving space realises an additional reduction of per capita energy demand, even though this key figure has been adopted political discussions.

On the downside, the building code recast in 2014 failed to increase the ambition level for energetic retrofit, which showed that regulations with regard to ambitious retrofit face strong political opposition and is not easily implemented. However, the main argument is profitability which may be proven for more ambitious in growing cities in future research.

Opposite to growing cities, living space prices are low and use intensity increasing in shrinking cities. Can people simply afford more living space?

An analysis of the processes shows, that the increased use intensity in shrinking cities is not a matter of affording more space but a matter of losing household members. When young people move away from their families they decrease the household size but not the used m^2 per person increases. When young people move away from a shared apartment they intermediately reduce the household size but may eventually be replaced, however the total number of people in shared apartments - that are mostly large households - decreases, hence the average household size decreases. The same situation applies to families, when they move away, they reduce the average household size.

Resulting from all migration types, the decreased use intensity, i.e. the increased living space per person, does not develop because of people moving into larger apartments. It evolves naturally due to the mainly young age of the migrating people. This insight leads to a conclusion for the design of potential policies, namely that a price signal will not change the amount of used floor area within shrinking cities.

Instead, policies could encourage sharing spaces, i.e. the rearrangement of single-family buildings to contain more living units. To reduce energy demand it is also helpful to rearrange the heating circuits to exclude unused areas. The detailed policy designs still need to be assessed and also the optimal policy mix requires further analysis.

Further options for efficient use of retrofit investments may be the concentration on buildings that offer high energy savings and demand a low investment. Multi-family buildings around the city centres are likely more advantageous for energy retrofit than single-family homes in the suburbs or historical buildings within the centres. Such multi-family homes usually follow a uniform architecture and have a better volume to surface ratio. As a result, their retrofit can be anticipated to provide more energy savings per invested Euro. An assessment of distinguished energy retrofit by building type could provide the decomposition of necessary measures with respect to climate goals.

The policy design is suggested on an aggregate level and needs to be refined with regard to the incremental increase of the ambition level at rising price levels. Within the scope of this work the ambition level of the renovations was not differentiated in detail to the growth rates within the cities. In fact, the renovation pathway was differentiated by strongly growing, slowly growing and shrinking cities. However, the ambition level should be adjusted for the profitability within the different real estate market conditions. What ambition level is profitable under which market conditions could be subject of future research. As a supporting fact, Michelsen, Zumbro, and Claudy, 2012, p. 305 found empirical evidence for the investors preference and increased investment in locations with high rental profits.

Political barriers may challenge the implementation of the suggested policy design. Though necessary for climate conservation, an increase of the ambition level for energetic retrofit has proven to be very hard.

The building code recast within the energy savings ordinance[78] failed to include an increased ambition level for energy retrofit. Although the current election programs of all major national parties contain a acknowledgement and adhere to the Paris Agreement, the political measures to get there are unclear and disputed. The CDU of North Rhine-Westphalia even suggested to set out the building code. Without prove of the profitability of an increased ambition level, however, there good reasoning for such policy adjustments to be implemented, as the design of policies specific to different cities by their development supports the profitability concern within the current legislation.

Containing the use intensity within shrinking cities may first appear to be challenging as the concerned people do not move and do not involve in a market transaction. They - mostly parents and old people - simply remain within their living units as the youngster move out or simply the surrounding ages and turns into smaller households. For shrinking cities various other instruments, as the following, may accompany the renovation activity and strongly support the savings. (a) an emphasis on inner development to gain attractiveness for the city center and increase its density, (b) the more efficient use of space (c) Single family home owners there should be encouraged to share their homes and supported in making the necessary changes. (d) If they are unable to share, due to age or lack of financing, other non-financial measures may be supported including the adjusted heating behaviour, i.e. partial heating. The single-family home where children moved out is not heated completely and informational measures may help the owner-occupiers to reduce the energy demand further. Energy can be conserved by adjusting the heating circuits which requires according information programs and training for local craftsman. Small technological energy saving innovations can evolve for these cases, if market conditions are attractive. Further research is needed for shrinking cities and regions to design these low cost but effective policies that encourage the reduction of heated area per person.

The reduced energy retrofit within shrinking cities reflects that within areas where limited financial means meet low living space demand are likely to lead to a lower retrofit activity and the suggested non-financial energy saving measures are more likely to be adopted.
Simultaneously, the investors in shrinking cities need to be especially well informed about the urban planning including future infrastructure changes. The retrofit projects conducted within the shrinking cities is riskier than within a prospering city with a stable real estate market. As a result, these investments are under more diligent review by banks and investors, as the risk of failure in payback is higher. Therefore, these investors or owners need to know if his property and building lies within an area of the city that will be part of the denser center with access to schools, shopping, public transport. On the other hand, the building will be part of a suburban area with removal of infrastructure as bus lines and schools. Regardless of the uncertainties connected to urban planning, the owner may want to adjust his investment decision.

[78] German: Energieeinsparverordnung (EnEV); BMWi, 2013

Bringing down the greenhouse gas emissions of buildings requires a tremendous effort of energy saving measures within buildings. The policy that is currently in place does not induce renovation rates and depths needed to accomplish climate policy goals. This work explores opportunities to adjust energy policies for buildings to population growth processes. These adjustments are then evaluated by quantifying their impact on energy savings and necessary investments.

To determine starting points for such energy policy adjustments, the potential influences of growth and shrinkage on energy demand in buildings were identified. The influences were parametrized based on big German cities. A regression facilitated this quantification and evidenced a negative correlation between population growth and floor area demand. To assess a future impact of policy adjustments, policy pathways were then designed to achieve climate policy targets. In a third step, these policy pathways were transferred to the cities and turned into new scenario when equipped with the previously parametrized growth influences. An analysis of these scenarios revealed the impact of the growth factors and the policy pathways. A cluster analysis of the cities additionally allowed to eliminate the building stock influence and isolate the growth impact. Finally, the adjusted policies were designed by assigning these scenarios and policy pathways to the cities based on their growth development.

8.1 Impact of demographic change

The quantification of the impact on energy demand and investments was successfully conducted considering the growth factors quantified in chapter 5. These factors comprise the migration related change in use intensity and the distribution of vacancy in mainly multi-family buildings.
At an overall population growth of 1.48% in big German cities the energy demand increases by only 1.14% and the investment in energy measures in buildings increases by 1.54%, in the GRIN scenario that considers the following implications of migration factors:

- the use of new buildings in growing cities instead of old buildings in shrinking cities,
- the use of more floor area per person in shrinking cities: +2.41 m^2,
- the use of less floor area per person in growing cities, [79] : -0.28 m^2
- the distribution of vacancy to middle-aged multifamily buildings.

The effect of the use intensity change is isolated when comparing the scenarios GRIN and GROW, cf. figure 20 (p. 67). The migration related change in use intensity leads to an additional increase of 1.7% in energy demand and of 2% in energy retrofit investment. [80].

The mere migration-related impact is rather small compared to the difference between policy scenarios. The implications of migration decrease the total energy demand of all big German cities by about 1.7%. In comparison, more ambitious policy pathways reduce the total energy demand by 10% and 21%, comparing the CP80 GRIN and the CP95 with the BAU GRIN respectively, cf. table 20 (p. 68).

[79] The changes in floor area are averages over all growing and shrinking cities and depend on the population growth rate in those cities, see also table 56.

[80] This is the share of the retrofit investment that is related to energy saving measures in existing and new buildings, cf. table 20

Energy targets for cities are more suitable when tailored to population growth can be shown within the results on page 60. The impact of demographic change, the buildings stock composition and the current energy demand level resulted in a difference of up to 10%-points (as shown in figure 16 (a)). Hence, a city's energy saving targets may be out of reach or contain less than the desired ambition level when not adjusted to population growth.

8.2 Effect of integrated policies

A policy that is adjusted for population growth and shrinkage should induce more efficient use of energy investments in buildings, according to the results. Within this analysis, the renovation ambition and use intensity change are adjusted based upon the net migration within big German cities. Within these adjusted scenarios a reduction of the energy demand of 2,2% was accompanied by a reduction of about 10% of investments for energy measures in buildings. To implement such scenarios it is necessary to conduct very ambitious renovations in growing cities with a high price level in the rental and real estate market. Such renovations deliver energy savings and are profitable within growing markets today. Another key measures is to contain the increase in heated floor space per person in shrinking cities.

Compared to the 21% energy savings that are achieved, switching from the BAU to the CP95 policy pathway, the 2.2% decrease in energy demand is small but much more cost efficient. Whereas a policy pathway switch requires an investment increase of 153% the migration-adjusted policy design offers at least a 10.3% decrease in investments.

The adjustment of policy design should rather be seen as a mean to achieve these policy pathways than as an additional measure. The policy pathways were projected based on Germany's climate policy goals. They show how much effort is needed in buildings to achieve climate policy goals, cf. section 2.1. As these pathways are normative, they show a strong increase in renovation rate and renovation depth which requires to overcome monetary and non-monetary barriers. The adjustment of the policy design and mix (regulations, financial and informational measures discussed in section 7.3 (p. 70) to the local market (price levels) and social (age structure) conditions could help to resolve these barriers. Moreover, the migration is happening without political effort and offers the starting or trigger points presented in chapter 7 to access economic energy saving potentials.

The work in hand provides evidence that the effective adjustment of the renovation ambition to the growth and shrinkage of cities results in lower energy demand at a lower total investment, cf. section 7.2.

8.3 Reviewing method and approach

The research question was approached by a combination of different methods: a cluster analysis to eliminate the building stock influence, a regression analysis to parametrize growth factors, an application of a building energy model to create policy pathways. The scenarios were then built by combining policy pathways, growth factors and city building stock data. A scenario analysis finally facilitated the quantification of the impact of growth and of adjusted policies.

This method combination was carefully chosen to obtain an answers to the research questions. A more centralized approach would integrate the different steps, for example, into the existing building model. Such an integrated model facilitates the repetition of the analysis for other data sets and parameters. The following paragraphs further discuss an alternative integrated approach.

Cities and their population growth could be integrated into the building energy model. To gain additional results with this step, further empiric data would be necessary to appropriately reflect the modernization of each city's building stock. As the number and degree of renovation activities is not uniformly surveyed within Germany, such integration would need an in-depth review of the energetic condition of the building stock in each of the 76 big German cities. This large effort had drawn the focus away from the research question and the additional information gain had been limited.

The integration of the growth factors into the energy building model does not provide an additional benefit to the results and the regression would still be necessary. The main benefit of the energy building model used is that energy demand and the single investment decisions, are calculated bottom-up based on the cost of energy and technology for each time period. The population growth itself would not change any of these parameters, which is why an integration of the growth factors does not provide added value to the results.

The scenario analysis offers the possibility to compare model results when changing only the factors under review. As the ability of a model to represent reality's processes is limited by nature, it will always lack behind in predicting complex processes, as the future energy demand development within a building stock. In this work, scenarios with and without population growth impact are analysed in chapter 6.1 and compared to adjusted policy designs in chapter 7. This approach allows to quantify the growth impact as a difference between scenarios The scenario analysis is therefore a suitable method to assess the impact of growth and of adjusted policies on the energy savings and investments in cities.

The approach includes transferring Germany's energy projection on growing and shrinking cities using specific energy consumption for each building segment. This transfer indirectly contains the assumption that the renovation activity is not significantly influenced by population growth. In contrast to this assumption, a probably weaker economic situation in shrinking regions may defer the investment intensive energetic renovations. As empirical research of this growth effect is still outstanding, the assessment in hand is conducted assuming growth independent renovation activity in chapter 6.1. This aspect finds consideration within the policy designs in chapter 7 in the form of adjusting the renovation ambition to the population growth of a city.

The data and assumptions are limited in their accuracy. The main data weakness lies within the missing renovation rate and renovation depth data, which are not gathered in a unified way across federal "Länder". The energy performance of the building stock and its improvement can thus not be monitored. It is possible that the fear of top-down control by the German or European institutions hampers local, regional and "Länder" administrations and politicians share for example for the energy performance certificates[81] in a countrywide database.
Another uncertainty arises from the the time frame until 2030. The development of retrofit technologies and costs is unknown. As there are a variety of options to achieve energy savings the costs vary strongly. Both of these uncertainties likely have an impact on the result of energy pathway projections.

A transition of results to other cities is highly dependent on the requirements and implementation of the building code (EnEV). Due to the dominant replacement effect by new construction, the energy saving

[81] German: Energieausweise

and the needed investment largely depend on the minimum requirements for new buildings. Within Germany the results may thus be transferable even to rural regions. For application in other European countries a comparison of building codes and renovation markets is necessary. Due to the energy impact of the building stock the quantification is not may be transferable. The approach however is suited be used for other building stocks and retrofit markets.

8.4 Outlook

The adjustment of energy policy in buildings to population growth is a small part of a big puzzle. The comprehensive integration of ecological (energy) and societal considerations into urban planning connotes a big potential for energy saving measures that is otherwise inaccessible. For example, when it comes to grid-based energy and heat transport or the ventilation of a city, urban planning today shapes the choices of tomorrow. How much heat will be demanded in the future and which supply technologies are available in a city is subject to long term planning. The added value of an integrated urban planning that includes considerations of ecology (and energy as one part of it) and societal developments yet needs evaluation. Meanwhile the processes of such integration is being assessed within existing European administrations and first experiences are made within the "Urban Learning" project[82].

The suggested approach forms a solid basis to be extended for quantification the impact of growth driven real estate price changes on renovation activity. The integration of price drivers into energy building modelling would then require detailed data on the price level changes within the rental and real estate market. Such an analysis could provide helpful advice for the detailed design of the suggested policy adjustment.

The approach at hand is suitable to perform an assessment and sensitivity for population growth, for example on the basis of new population projections that reflect the current and future refugee immigration. As ongoing demographic change contains a change in the population structure exceeding the mere growth. The effect of an ageing and culturally more diverse population may affect the heating behaviour and the development of the national energy consumption. Simultaneously, the investment behaviour and the willingness to invest in ones own property varies by age and nationality. Both aspects were not subject within this but may be analysed in future research on the basis of this research.

Empirical studies offer the opportunity to enhance the data basis on the effect of partial heating and heating behaviour with respect to age and the remanence effect. These results would facilitate the detailed design of policy adjustments to local growth. Within city-based case studies the developed growth-adjusted policies could subsequently prove their validity in practice.

[82] www.urbanlearning.eu/

Achtnicht, Martin and Reinhard Madlener (2014). Factors influencing German house owners' preferences on energy retrofits. In: Energy Policy 68.12, pp. 254–263. ISSN: 03014215. DOI: 10.1016/j.enpol.2014.01.006 (cit. on p. 25).

Aitchison, John (1986). The statistical analysis of compositional data. In: p. 420 (cit. on p. 12).

Aksoezen, Mehmet et al. (2015). Building age as an indicator for energy consumption. In: Energy and Buildings 87, pp. 74–86. ISSN: 03787788. DOI: 10.1016/j.enbuild.2014.10.074 (cit. on p. 22).

Atanasiu, Bogdan et al. (2014). Overview of the Eu-27 Building Policies and Programs. Factsheets on the Nine Entranze Target Countries. Tech. rep., p. 256 (cit. on p. 36).

Bacher, Johann (1994). Clusteranalyse: Anwendungsorientierte Einführung. München: Oldenbourg. ISBN: 3-486-22832-3 (cit. on pp. 14–15).

Bacher, Johann, Andreas Pöge, and Knut Wenzig (2010). Clusteranalyse: Anwendungsorientierte Einführung in Klassifikationsverfahren. Oldenbourg Verlag. ISBN: 3486710230 (cit. on p. 14).

Backhaus, Klaus (2011). Multivariate Analysemethoden: Eine anwendungsorientierte Einführung. 13., übe. Springer-Lehrbuch. Berlin [u.a.]: Springer. ISBN: 978-3-642-16490-3 (cit. on p. 14).

Banse, Juliane and Karl-Heinz Effenberger (2006). Deutschland 2050: Auswirkungen des demographischen Wandels auf den Wohnungsbestand. IöR (cit. on pp. 51, 53).

Bertelsmann Stiftung (2014). Datenlieferung für deutsche Großstädte (cit. on pp. 49–50, 53–54, 63).

Bettgenhäuser, Kjell (2013). Integrated assessment modelling for building stocks: A technical economical and ecological analysis. 1. Aufl. Bonn: Ingenieurwiss. Verl. ISBN: 978-3-944653-01-3 (cit. on pp. 5, 33).

BMUB (2015). Kyoto Protokoll (cit. on p. 3).

BMVBS, ed. (2012). Energiebericht 2012 (cit. on p. 25).

– ed. (2013). Maßnahmen zur Umsetzung der Ziele des Energiekonzeptes im Gebäudebereich–Zielerreichungsszenario (cit. on pp. 25, 35).

BMWi and BMUB, eds. (2010). Energiekonzept: für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung (cit. on pp. 25–26, 29, 31).

BMWi, Bundesministerium für Wirtschaft und Technologie (2017). Bundeshaushaltsplan 2017. Tech. rep., p. 212 (cit. on p. 28).

– (2015). Energie der Zukunft. Tech. rep., p. 172 (cit. on p. 4).

– (2013). Zweite Verordnung zur Änderung der Energieeinsparverordnung. In: 2013.67, pp. 3951–3990 (cit. on pp. 31, 70).

Böhmer, Michael et al. (2011). Volkswirtschaftliche Bewertung der EnEV 2009 Basel/Berlin, Abschlussbericht der Studie. Ed. by Bundesarchitektenkammer e.V et al. (cit. on p. 25).

Boogaart, Gerald K van den and Raimon Tolosana-Delgado (2013). Analyzing compositional data with R. Use R! Berlin and New York: Springer. ISBN: 3-642-36808-5 (cit. on p. 12).

Brannath, Werner and Andreas Futschik (2001). Statistik für Wirtschaftswissenschaftler : eine Einführung anhand von Beispielen. [3. Aufl.] UTB ; 2207 : Wirtschaftswissenschaften, Statistik. Wien: WUV-Univ.-Verl. ISBN: 3-85114-562-3; 3-8252-2207-1 (cit. on p. 43).

Braun, R, P Heising, and P Schwede (2014). Aktuelle und zukünftige Entwicklung von Wohnungsleerständen in den Teilräumen Deutschlands: Datengrundlagen, Erfassungsmethoden und Abschätzungen. In: (cit. on p. 51).

Braun, Reiner (2010). Analyse des Wohnungsmarktes in Deutschland. In: Aspekte des Wohneigentums. Berlin: Kerstin Funk (Hrsg.), 15–51 of 261 (cit. on p. 41).

Bräuninger, Michael and Alkis Otto (2006). Die zukünftige Entwicklung auf den Wohnungsmärkten in Deutschland. In: Wirtschaftsdienst 86.8, pp. 532–537. ISSN: 0043-6275. DOI: 10.1007/s10273-006-0554-4 (cit. on p. 53).

Bundesregierung (2015). Asylverfahrensbeschleunigungsgesetz. In: Bundesgesetzblatt 2015.40, pp. 1722–1735 (cit. on pp. 31, VI).

Bundesregierung (2007). Das Integrierte Energie- und Klimaprogramm der Bundesregierung. In: p. 98 (cit. on p. 4).
– (2016a). Die deutsche Nachhaltigkeitsstrategie. Tech. rep. Berlin, p. 260 (cit. on p. 39).
– (2008). Gesetz zur Förderung Erneuerbarer Energien im Wärmebereich (Erneuerbare-Energien-Wärmegesetz - EEWärmeG). In: Bundesgesetzblatt 2008.36, pp. 1658–1665 (cit. on pp. 31, VI).
– (2016b). Klimaschutzplan 2050 - Klimaschutzpolitische Grundsätze und Ziele der Bundesregierung (cit. on p. 4).
– (2014). Nationaler Aktionsplan Energieeffizienz (NAPE): Mehr aus Energie machen: Ein gutes Stück Arbeit. Ed. by BMWi. Berlin (cit. on p. 4).
Bürger, Veit et al. (2012). Energieeinsparquote für Deutschland? Bewertung des Instruments der Energieeinsparquote (Weiße Zertifikate) auf seine Eignung als Klimaschutzinstrument für Deutschland. Ed. by Öko-Institut e.V. (cit. on p. 36).
Bürger, Veit et al. (2013). Konzepte für die Beseitigung rechtlicher Hemmnisse des Klimaschutzes im Gebäudeberech. Tech. rep. Berlin: Umweltbundesamt, p. 392. DOI: 10.4337/9781781002490.00013 (cit. on p. 36).
Chatterjee, Samprit, Mark S Handcock, and Jeffrey S Simonoff (1995). A casebook for a first course in statistics and data analysis. New York [u.a.]: Wiley. ISBN: 0-471-11030-2 (cit. on p. 43).
Deschermeier, Philipp and Ralph Henger (2015). Die Bedeutung des zukünftigen Kohorteneffekts auf den Wohnflächenkonsum. In: IW-Trends – Vierteljahresschrift zur empirischen Wirtschaftsforschung 42.3, pp. 23–39. DOI: http://dx.doi.org/10.2373/1864-810X.15-03-02 (cit. on pp. 29, 41, 52).
Destatis (2011). Gemeindeverzeichnis Jahresausgabe. Tech. rep. 0 (cit. on p. 19).
Diefenbach, Nikolaus and Rolf Born (2007). Basisdaten für Hochrechnungen mit der Deutschen Gebäudetypologie des IWU. In: pp. 1–2 (cit. on p. 30).
Diefenbach, Nikolaus and Tobias Loga (2011). Basisdaten für Hochrechnungen mit der Deutschen Gebäudetypologie des IWU: Neufassung August 2011. Ed. by IWU. Darmstadt (cit. on pp. 23–24, 53).
Diefenbach, Nikolaus et al. (2010). Datenbasis Gebäudebestand: Datenerhebung zur energetischen Qualität und zu den Modernisierungstrends im deutschen Wohngebäudebestand. Darmstadt (cit. on p. 24).
Diefenbach, Nikolaus et al. (2012). Monitoring der KfW-Programme "Energieeffizient Sanieren" und "Energieeffizient Bauen" 2011. Ed. by KfW Bankengruppe. Darmstadt (cit. on p. 27).
– (2014). Monitoring der KfW-Programme "Energieeffizient Sanieren" und "Energieeffizient Bauen" 2013. Ed. by KfW Bankengruppe. Darmstadt (cit. on p. 27).
– (2015). Monitoring der KfW-Programme "Energieeffizient Sanieren" und "Energieeffizient Bauen" 2014. Ed. by KfW Bankengruppe. Darmstadt (cit. on p. 27).
Diefenbach, Nikolaus et al. (2016). Monitoring der KfW-Programme Energieeffizient Sanieren und Energieeffizient Bauen 2015. Darmstadt, Germany (cit. on p. 24).
Döring, Ulrike et al. (2013). Politikszenarien für den Klimaschutz VI: Treibhausgas-Emissionsszenarien bis zum Jahr 2030: Forschungskennzahl 3709 41 109. Ed. by Umweltbundesamt. Dessau-Roßlau (cit. on p. 5).
Dunkelberg, Elisa and Julika Weiß (2016). Ökologische Bewertung energetischer Sanierungsoptionen, Gebäude-Energiewende, Arbeitspapier 4. Tech. rep. Berlin, p. 64 (cit. on p. 29).
EC, European Parliament and the and Council (2009). 406/2009/EC EU decision on the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020 (cit. on p. 3).
Effenberger, Karl-Heinz, Juliane Banse, and Holger Oertel (2014). Deutschland 2060: Die Auswirkungen des demographischen Wandels auf den Wohnungsbestand. Vol. 39. Reihe Wissenschaft. Stuttgart: Fraunhofer IRB Verl. ISBN: 9783816792819 (cit. on pp. 10, 41).
Egozcue, Juan José et al. (2003). Isometric logratio transformations for compositional data analysis. In: Mathematical Geology 35.3, pp. 279–300 (cit. on p. 13).
Enseling, Andreas (2014). Investive Mehrkosten bei Neubau und Sanierung. Darmstadt (cit. on p. 4).

EU (2014). 2030 climate and energy framework (cit. on p. 3).
– (2017a). Buildings under the EED (cit. on p. 4).
– (2017b). Buildings website at EC Energy (cit. on p. 3).
– (2016). Intended Nationally Determined Contribution of the EU and its Member States (cit. on p. 3).
Feller, William (1971). An introduction to probability theory and its applications. 2. ed. Vol. 2: New York, NY: Wiley. ISBN: 0-471-25709-5; 978-81-265-1806-7 (cit. on p. 48).
Feser, Daniel, Nora Vogt, and Stefan Winnige (2015). ökonomische Rahmenbedingungen der energetischen Gebäudesanierung (cit. on p. 25).
Friedrich, M et al. (2007). CO2-Gebäudereport 2007, im Auftrag des Bundesministeriums für Verkehr, Bau und Stadtentwicklung (BMVBS). In: Fraunhofer Institut für Bauphysik, Stuttgart (cit. on p. 25).
Garrecht, H. and G. Pfeifer (2016). Energieeffiziente Fassaden aus Leichtbeton mit haufwerksporigem Gefüge; Kopplung von Fassadenluftkollektoren im Vergleich zu monolithischen und mit WDVS gedämmten Konstruktionen - Energy-efficient facades from no-fines lightweight concrete : coupling with. In: Betonwerk und Fertigteiltechnik International (2016) 2, pp. 122–126 (cit. on p. 6).
Garrecht, Harald (2009). Energetische Sanierung der Gebäudehülle – Möglichkeiten und bauphysikalische Grenzen. In: 1. Darmstädter Ingenieurkongress - Bau und Umwelt. Ed. by Dipl.-Ing Berenike Astheimer-Heger. Darmstadt: Prof. Dr.-Ing. Hans Joachim Linke, p. 1 (cit. on p. 35).
Geppert, Kurt and Martin Gornig (2010). Mehr Jobs, mehr Menschen: Die Anziehungskraft der großen Städte wächst. In: Wochenbericht des Deutschen Instituts für Wirtschaftsforschung (DIW) 77.19, pp. 2–10 (cit. on p. 54).
Günthner, Stephan (2012). Zukünftige Herausforderungen für Wohnungsmärkte in wachsenden Städten. In: ÖPNV und wohnungsnahe Versorgung – Attraktivitätsfaktoren großer Städte. Ed. by Brigitte Adam and Gabriele Sturm. Bonn, pp. 73–79 (cit. on p. 40).
Haller, Markus et al. (2015). Überblick über vorliegende Szenarienarbeiten für den Klimaschutz in Deutschland bis 2050. In: pp. 1–88 (cit. on p. 5).
Hansen, Patrick (2009). Entwicklung eines energetischen Sanierungsmodells für den europäischen Wohngebäudesektor unter dem Aspekt der Erstellung von Szenarien für Energie-und Co2-Einsparpotenziale bis 2030. Vol. 48. Jülich: Forschungszentrum Jülich (cit. on p. 33).
Hohn, Uta (1991). Die Zerstörung deutscher Städte im Zweiten Weltkrieg. In: Regionale Unterschiede in der Bilanz der Wohnungstotalschäden und Folgen des Luftkrieges unter bevölkerungsgeographischem Aspekt (cit. on p. 20).
Höhne, Niklas, Sebastian Sterl, and Hanna Fekete (2015). How much more could Germany achieve through non-state action? In: (cit. on p. 26).
Hoier, Anna et al. (2013). Energetische Gebäudesanierung in Deutschland (cit. on p. 26).
Holm, Andreas and Christoph Sprengard (2013). Dämmstoffe als Baustein der Energiewende. In: Energieeffizienz in Geböuden. Jahrbuch. Berlin: VME-Verlag und Medienservice Energie, pp. 139–146 (cit. on p. 29).
IPCC et al. (2014). Summary for Policymakers. Tech. rep. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, pp. 1–33. DOI: `10.1017/CBO9781107415324`. arXiv: `arXiv:1011.1669v3` (cit. on p. 1).
IWU (2003). Deutsche Gebäudetypologie: Systematik und Datensätze. Darmstadt (cit. on pp. 11, 23).
Kalusche, W (2004). Technische Lebensdauer von Bauteilen und wirtschaftliche Nutzungsdauer eines Gebäudes: Festschrift zum 60. Geburtstag von Professor Dr. Hansruedi Schalcher Eidgenössische Technische Hochschule Zürich (cit. on p. 24).
KfW, ed. (2011). Die energetische Qualität des Wohnungsbestandes (cit. on p. 25).
Kleemann, Manfred and Patrick Hansen (2005). Evaluierung der CO2-Minderungsmassnahmen im Gebäudebereich. Jülich: Forschungszentrum, Zentralbibliothek. ISBN: 3-89336-419-6 (cit. on pp. 24–25, 36).
Kranzl, Lukas et al. (2013). Renewable heating: Perspectives and the impact of policy instruments. In: Energy Policy 59, pp. 44–58. ISSN: 03014215. DOI: `10.1016/j.enpol.2013.03.050` (cit. on p. 30).

Leutner, Bernd et al. (2011). Demografischer Wandel und Entwicklung des Immobilienmarkts in peripheren ländlichen Regionen Ostdeutschlands. Tech. rep., p. 9 (cit. on p. 41).

Linke, Hans-Joachim (2013). Siedlungsumbau aufgrund des demographischen Wandels. In: Land Management : Potential , Problems and Stumbling Blocks Landmanagement : Potenzial , Problemfelder. Ed. by Erwin Hepperle et al. vdf Hochschulverlag, pp. 107–120. ISBN: 9783728134790. DOI: 10.3218/3480-6 (cit. on p. 51).

Loga, Tobias et al. (2007). Querschnittsbericht Energieeffizienz im Wohngebäudebestand: Techniken, Potenziale, Kosten und Wirtschaftlichkeit. Darmstadt, Germany: Verbandes der Südwestdeutschen Wohnungswirtschaft e.V. (VdW südwes, p. 44 (cit. on p. 5).

Mackensen, Eva von (2007). Wohnen in der Stadt und demographischer Wandel. Anfragen an die Stadtplanung. In: Die Stadt in der Sozialen Arbeit. Springer, pp. 316–328 (cit. on p. 40).

Mäurer, Andreas and Martin Schlummer (2014). Recyclingfähigkeit von Wärmedämmverbundsystemen mit Styropor. In: Mineralische Nebenprodukte und Abfälle - Aschen, Schlacken, Stäube und Baurestmassen. Ed. by Thomé-Kozmiensky. Berlin: TK-Verlag. Chap. Berliner K, pp. 449–455. ISBN: 978-3-944310-11-4 (cit. on p. 29).

McKenna, Russell et al. (2013). Energy efficiency in the German residential sector. A bottom-up building-stock-model-based analysis in the context of energy-political targets. In: Building and Environment 62, pp. 77–88. DOI: 10.1016/j.buildenv.2013.01.002 (cit. on p. 25).

Michelsen, Claus, T Zumbro, and M Claudy (2012). Von "grünen Investitionen "und "glühenden Landschaften ": Was sind die Treiber des Heizenergieverbrauchs in Mehrfamilienhäusern?–Ergebnisse auf Grundlage des ista-IWH-Energieeffizienzindex. In: Wirtschaft im Wandel 18.10, pp. 300–307 (cit. on p. 69).

Monkkonen, Paavo, Kelvin Wong, and Jaclene Begley (2012). Economic restructuring, urban growth, and short-term trading: The spatial dynamics of the Hong Kong housing market, 1992–2008. In: Special Section on Asian Real Estate Market 42.3, pp. 396–406. ISSN: 0166-0462. DOI: 10.1016/j.regsciurbeco.2011.11.004 (cit. on p. 53).

Mosler, Karl C and Friedrich Schmid (2003). Beschreibende Statistik und Wirtschaftsstatistik : mit 2 Tab. Springer-Lehrbuch. Berlin: Springer. ISBN: 3-540-00552-8 (cit. on pp. 44–45).

– (2011). Wahrscheinlichkeitsrechnung und schließende Statistik. 4., verb. Springer-Lehrbuch. Berlin: Springer. ISBN: 978-3-642-15009-8 (cit. on pp. 43, 47).

Müller, Andreas (2015). Energy Demand Assessment for Space Conditioning and Domestic Hot Water: A Case Study for the Austrian Building Stock. PhD thesis, p. 285. DOI: 10.13140/RG.2.1.1191.9529 (cit. on pp. 5, 26, 31, 33).

Müller, Ulrich, Bernhard Nauck, and Andreas Diekmann (2000). Handbuch der Demografie (Bd. 1: Modelle und Methoden; Bd. 2: Anwendungen). Heidelberg: Berlin: Springer, p. 728. ISBN: 978-3540661061 (cit. on p. 8).

Neuhoff, Karsten et al. (2011). Energetische Sanierung: Handlungsbedarf auf vielen Ebenen. In: DIW-Wochenbericht 34, pp. 3–13 (cit. on p. 2).

Pawlowsky-Glahn, V and J J Egozcue (2006). Compositional data and their analysis: an introduction. In: Geological Society, London, Special Publications 264.1, pp. 1–10 (cit. on p. 12).

Pehnt, Martin (2010). Energieeffizienz. Berlin, Heidelberg: Springer Berlin Heidelberg. ISBN: 978-3-642-14250-5. DOI: 10.1007/978-3-642-14251-2 (cit. on p. 25).

Pfeiffer, Martin, Dirk Fanslau-Görlitz, and Julia Zedler (2008). Nutzungsdauertabellen für Wohngebäude: Lebensdauer von Bau- und Anlagenteilen. Berlin: Bauwerk. ISBN: 978-3-89932-192-0 (cit. on p. 26).

Prognos AG and Öko-Institut e.V. (2009). Modell Deutschland: Klimaschutz bis 2050: Vom Ziel her denken. Ed. by World Wide Fund for Nature Deutschland. Frankfurt am Main (cit. on pp. 5, 56).

Regionalstatistik (2017). table 182-21-5-B. Tech. rep. (cit. on p. 2).

Repenning, Julia et al. (2014). Klimaschutzszenario 2050: 1. Modellierungsrunde: Studie im Auftrag des Bundesministeriums f{ü}r Umwelt, Naturschutz, Bau und Reaktorsicherheit. In: Runde 1 (cit. on pp. 5, 29).

Rohde, Clemens et al. (2012). Behavioural Climate Change Mitigation Options - Domain Report Housing. Tech. rep. January. Delft: CE Delft; Fraunhofer ISI; LEI, p. 102. DOI: Publicationcode:12.7316.01 (cit. on pp. 56, 64).

Rohr-Zänker, Ruth (2014). Wohnungsmärkte im Wandel. Tech. rep. Hannover, pp. 1–12 (cit. on p. 40).

Schiffers, Bertram (2009). Immobilienmarkt in schrumpfenden Städten. In: Verfügungsrechte im Stadtumbau. Ed. by Bertram Schiffers. Quartiersforschung. Wiesbaden: VS Verlag für Sozialwissenschaften, pp. 27–48. ISBN: 978-3-531-16560-8. DOI: 10.1007/978-3-531-91497-8_2 (cit. on p. 39).

Schlesinger, Michael et al. (2014). Entwicklung der Energiemärkte – Energiereferenzprognose. Tech. rep. 57. Basel/Köln/Osnabrück: Prognos, p. 42 (cit. on p. 5).

Schlomann, Barbara et al. (2012). Kosten-/Nutzen-Analyse der Einführung marktorientierter Instrumente zur Realisierung von Endenergieeinsparungen in Deutschland: Endbericht an das Bundesministerium für Wirtschaft und Technologie (BMWi). Projektnummer 36/10. Karlsruhe, Freiburg, and Berlin (cit. on p. 36).

Simon-Philipp, Christina and Karin Hopfner (2013). Das Wohnungsbauerbe der 1950er bis 1970er Jahre - Perspektiven und Handlungsoptionen für Wohnquartiere. Ludwigsburg (cit. on pp. 41, 51).

Spars, Guido, ed. (2006). Wohnungsmarktentwicklung Deutschland: Trends, Segmente, Instrumente. Vol. 58. ISR-Diskussionsbeiträge. Universitätsverlag der TU Berlin. ISBN: 3798320152 (cit. on p. 53).

– (2012). Zukünftige Herausforderungen für Wohnungsmärkte in wachsenden Städten. In: Die Attraktivität großer Städte - ökonomisch, demografisch, kulturell. Ed. by Brigitte Adam and Gabriele Sturm. Bonn, pp. 56–66 (cit. on p. 40).

Sprengard, Christoph, Treml Sebastian, and Andreas H. Holm (2013). Technologien und Techniken zur Verbesserung der Energieeffizienz von Gebäuden durch Wärmedämmstoffe. Tech. rep., p. 283 (cit. on p. 29).

Statistisches Bundesamt (2011a). Bevölkerung in Städten in 2011 nach Zensus korrigiert. https://www.destatis.de/ (cit. on p. 50).

– (2011b). Demografischer Wandel in Deutschland - Bevölkerungs- und Haushaltsentwicklung im Bund und in den Ländern. Tech. rep. Wiesbaden, pp. 1–40 (cit. on p. 52).

– (2014). ZENSUS 2011 (2014) - Gebäudezahlen nach Baualtersklasse, Wohneinheiten, Außenwände und Eigentümerstruktur: database query on demand. Ed. by Statistisches Bundesamt (cit. on pp. 10, 50).

Steinbach, Jan (2016). Modellbasierte Untersuchung von Politikinstrumenten zur Förderung erneuerbarer Energien und Energieeffizienz im Gebäudebereich, Dissertation. Karlsruhe: Fraunhofer Verlag. ISBN: 9873839609873 (cit. on pp. 5, 30–31, 34–35).

Stieß, Immanuel and Elisa Dunkelberg (2013). Objectives, barriers and occasions for energy efficient refurbishment by private homeowners. In: Journal of Cleaner Production 48, pp. 250–259. ISSN: 09596526. DOI: 10.1016/j.jclepro.2012.09.041 (cit. on p. 25).

Stieß, Immanuel et al. (2010). Handlungsmotive,-hemmnisse und Zielgruppen für eine energetische Gebäudesanierung: Ergebnisse einer standardisierten Befragung von Eigenheimsanierern. Frankfurt am Main (cit. on p. 25).

Umweltbundesamt (2004). Flächenverbrauch, ein Umweltproblem mit wirtschaftlichen Folgen. Tech. rep. Hintergrundpapier. Berlin, p. 18 (cit. on p. 39).

– (2013). Weltweites „ Aus “ für Flammschutzmittel HBCD - Verbot wirkt nach einem Jahr Übergangsfrist. In: Presseinformation Nr 23 23, pp. 1–2 (cit. on p. 29).

Urban, Dieter (2011). Regressionsanalyse: Theorie, Technik und Anwendung. Ed. by Jochen Mayerl. Wiesbaden (cit. on pp. 43, 45, 47, 50).

Wietschel, Martin et al. (2010). Energietechnologien 2050 - Schwerpunkte für Forschung und Entwicklung: Politikbericht. ISI-Schriftenreihe Innovationspotenziale. Stuttgart: Fraunhofer Verlag. ISBN: 978-3-8396-0084-9 (cit. on p. 25).

Zwicker-Schwarm, Daniel et al. (2008). Wege zum nachhaltigen Flächenmanagement – Themen und Projekte des Förderschwerpunkts REFINA. Berlin (cit. on p. 39).

Doha Amendmend The Doha Amendment is an amendment to the Kyoto Protocol negotiated in Doha, Qatar in 2012. It includes a second commitment period from 2012 to 2020 and was ratified by 75 countries as of December 2016. Germany has not ratified.. 3

EEWärmeG Law to promote renewable energy for heating, see Bundesregierung, 2008 and Bundesregierung, 2015 Enacted in 2009, it includes a requirement to use renewable energy for heating in newly constructed buildings.. 31

EnEV Energy savings ordinance containing the building code which sets minimum energy requirements for new buildings, renovations and the replacement of single building parts. The maximum u-value is defined by building part and as the maximum heat transmittance for the complete envelope. The code applies in case of partial and complete retrofit.. 26, 28, 31, 33, 56, 73

INVERT/EE-Lab is a bottom up model to simulate the development of a building with regard to energy demand based on investor decisions. `www.invert.at`. 5, 30, 33, 35

KfW KfW originally abbreviated the "Kreditbank für Wiederaufbau" which can be translated to "credit bank for reconstruction", which was its original purpose. Currently, the long form is not used any more.. 26, 27

Kyoto Protocol An international agreement standing on its own, and requiring separate ratification by governments, but linked to the UNFCCC. The Kyoto Protocol, among other things, sets binding targets for the reduction of greenhouse-gas emissions by industrialized countries.. 3, VI

Paris Agreement The Paris Aggreement is an international climate agreement reached at the 21st Conference of the Parties to the 1992 UNFCCC in Paris 2015. It requires voluntary and nationally for GHG mitigation starting in 2020 and includes the adaptation and financing. As of December 2016 it was ratified by 132 countries.. 3

renovation rate In this research, the renovation rate is defined and interpreted as the share of the floor area renovated per year. Partial measures are combined to full renovation equivalents. The renovations include the exchange of windows, retrofit of the roof, walls and the floor as well as heating system and heating distribution system exchanges. This is in line with the definition employed in the context of German energy concept.. 24

UNFCCC United Nations Framework Convention on Climate Change. The treaty originated in the 1992 Earth summit in Rio de Janeiro and came into force in 1994. It sets the objective to stabilize greenhouse gas concentration and outlines how greenhouse gas limits can be negotiated. It forms the bases for international agreements on greenhouse gas mitigation, as achieved in Kyoto and Paris.. 3, VI

use intensity The floor area per person. The use of the term is contradictory as an increased use intensity indicates a more intense use of the floor area, while the m^2/cap value decreases.. 40

U-value Within the field of construction it resembles the thermal transmittance as it describes the energy loss through the building's envelope per area. It is measured in kWh/m^2. 28, 38, see

Acronyms

AFOLU Agriculture, forestry and other land use. 1

alr additive-log-ratio. 12

BMWi Federal Ministry for Economic Affairs and Energy (German: Bundesministerium für Wirtschaft und Energie). 4

clr centered-log-ratio. 12

EED Energy Efficiency Directive. 3, 4

EPBD Energy Performance in Buildings Directive. 3

GHG greenhouse gas. 3, VI

IEKP Integrated Energy and Climate Program. 4

MAP Marktanreizprogramm. 28

PCA principle component analysis. 14

SEE standard error of estimate. 43

UNFCCC United Nations Framework Conventions on Climate Change. 3

Table 21: data structure of census data per city

construction period	number of residential units	attachment type	number of buildings
before 1919	01	detached	...
before 1919	01	semi-detached	...
before 1919	01	row house	...
before 1919	01	other house	...
before 1919	02	detached	...
before 1919	02	...	...
before 1919	...	...	...
...	...	...	...
2009 and later	13 and more	other house	...

Table 22: population, floor area per person and their changes between 2005 and 2011

city	cluster id	municipal code	population 2011 [count]	population 2005 [count]	use intensity 2011 [m2/cap]	use intensity 2005 [m2/cap]	population growth 2005 – 2011 [%]	use intensity change 2005 – 2011 [%]
Berlin	1	11000000	326,002	216,636	38.0	38.4	3.4 %	-1.0 %
Chemnitz	1	14511000	240,543	245,703	39.5	39.7	-2.1 %	-0.5 %
Dresden	1	14612000	517,765	476,325	35.2	37.0	8.7 %	-4.9 %
Erfurt	1	16051000	201,952	198,186	36.1	37.0	1.9 %	-2.4 %
Halle	1	15002000	230,494	235,198	38.9	38.7	-2.0 %	0.5 %
Jena	1	16053000	106,428	103,429	35.5	35.0	2.9 %	1.4 %
Leipzig	1	14713000	510,043	478,016	39.3	41.0	6.7 %	-4.1 %
Magdeburg	1	15003000	228,910	223,327	36.6	37.0	2.5 %	-1.1 %
Potsdam	1	12054000	157,603	142,113	35.8	35.9	10.9 %	-0.3 %
Rostock	1	13003000	201,813	196,699	34.7	34.6	2.6 %	0.3 %
Bergisch Gladbach	2	5378004	109,026	109,135	45.9	44.2	-0.1 %	3.8 %
Bottrop	2	5512000	117,074	120,695	37.1	35.4	-3.0 %	4.8 %
Hamm	2	5915000	176,474	179,161	38.5	36.7	-1.5 %	4.9 %
Leverkusen	2	5316000	159,373	159,853	38.7	37.1	-0.3 %	4.3 %
Moers	2	5170024	103,831	106,603	36.4	35.0	-2.6 %	4.0 %
Heilbronn	3	8121000	116,716	113,980	38.5	38.4	2.4 %	0.3 %
Ingolstadt	3	9161000	126,076	119,503	40.0	38.8	5.5 %	3.1 %
Neuss	3	5162024	151,070	150,919	40.2	39.0	0.1 %	3.1 %
Oldenburg	3	3403000	157,706	153,710	44.4	43.3	2.6 %	2.5 %
Paderborn	3	5774032	143,174	138,600	40.8	40.1	3.3 %	1.7 %
Reutlingen	3	8415061	110,084	109,536	38.0	37.1	0.5 %	2.4 %
Wolfsburg	3	3103000	120,889	120,407	42.9	41.1	0.4 %	4.4 %
Bielefeld	4	5711000	327,199	331,845	38.2	36.4	-1.4 %	4.9 %
Bonn	4	5314000	307,530	292,607	38.7	38.9	5.1 %	-0.5 %
Erlangen	4	9562000	104,312	100,590	40.3	39.7	3.7 %	1.5 %
Fürth	4	9563000	116,640	112,805	40.4	39.6	3.4 %	2.0 %
Mainz	4	7315000	201,002	186,113	39.1	38.7	8.0 %	1.0 %
Münster	4	5515000	293,393	271,660	40.2	40.8	8.0 %	-1.5 %
Ulm	4	8421000	117,541	114,117	37.7	37.4	3.0 %	0.8 %
Würzburg	4	9663000	124,449	124,201	39.5	37.9	0.2 %	4.2 %
Augsburg	5	9761000	269,402	263,088	38.7	37.8	2.4 %	2.4 %
Düsseldorf	5	5111000	589,649	570,260	39.0	39.3	3.4 %	-0.8 %
Frankfurt am Main	5	6412000	676,533	632,865	36.1	36.1	6.9 %	0.0 %
Freiburg im Breisgau	5	8311000	214,234	200,032	34.6	35.1	7.1 %	-1.4 %
Hamburg	5	2000000	718,187	656,882	35.7	35.6	3.7 %	0.3 %
Hannover	5	3241001	509,485	499,985	40.7	40.8	1.9 %	-0.2 %
Heidelberg	5	8221000	148,415	142,024	37.1	37.4	4.5 %	-0.8 %
Karlsruhe	5	8212000	291,995	278,887	39.0	39.3	4.7 %	-0.8 %
Kiel	5	1002000	237,667	229,187	37.5	38.5	3.7 %	-2.6 %
Köln	5	5315000	013,665	966,316	37.4	37.2	4.9 %	0.5 %
Mannheim	5	8222000	291,458	284,627	38.9	39.0	2.4 %	-0.3 %
München	5	9162000	364,920	237,461	37.0	38.2	10.3 %	-3.1 %
Nürnberg	5	9564000	490,085	475,349	38.4	37.8	3.1 %	1.6 %
Offenbach am Main	5	6413000	114,855	111,835	34.5	34.6	2.7 %	-0.3 %
Regensburg	5	9362000	136,352	128,755	42.4	41.3	5.9 %	2.7 %
Stuttgart	5	8111000	591,015	569,379	35.9	35.9	3.8 %	0.0 %
Aachen	6	5334002	238,665	236,302	37.1	36.0	1.0 %	3.1 %
Braunschweig	6	3101000	243,829	239,283	41.7	41.6	1.9 %	0.2 %
Bremerhaven	6	4012000	108,139	112,294	43.5	42.1	-3.7 %	3.3 %
Darmstadt	6	6411000	145,845	137,072	39.8	40.4	6.4 %	-1.5 %
Dortmund	6	5913000	571,403	578,929	39.4	37.9	-1.3 %	4.0 %
Göttingen	6	3152012	116,052	116,870	38.6	37.1	-0.7 %	4.0 %
Hagen	6	5914000	187,333	198,656	42.0	39.1	-5.7 %	7.4 %
Kassel	6	6611000	191,854	189,767	39.5	39.3	1.1 %	0.5 %
Lübeck	6	1003000	210,679	211,951	38.9	38.0	-0.6 %	2.4 %
Ludwigshafen am Rhein	6	7314000	158,637	156,601	39.2	38.6	1.3 %	1.6 %
Trier	6	7211000	106,284	100,743	41.1	41.4	5.5 %	-0.7 %
Wiesbaden	6	6414000	270,952	266,161	38.8	38.3	1.8 %	1.3 %
Wuppertal	6	5124000	342,570	353,895	40.3	38.4	-3.2 %	4.9 %
Krefeld	7	5114000	221,864	225,472	41.3	40.0	-1.6 %	3.3 %
Mönchengladbach	7	5116000	254,834	259,505	39.6	38.0	-1.8 %	4.2 %
Mülheim an der Ruhr	7	5117000	166,804	170,035	43.2	41.1	-1.9 %	5.1 %
Oberhausen	7	5119000	210,256	216,982	36.8	35.1	-3.1 %	4.8 %
Osnabrück	7	3404000	154,513	154,051	41.4	40.5	0.3 %	2.2 %
Pforzheim	7	8231000	115,211	113,397	38.2	37.7	1.6 %	1.3 %
Recklinghausen	7	5562032	115,648	120,467	40.2	38.2	-4.0 %	5.2 %
Remscheid	7	5120000	110,132	117,412	41.7	38.7	-6.2 %	7.8 %
Solingen	7	5122000	155,080	159,383	37.4	35.6	-2.7 %	5.1 %
Bochum	8	5911000	362,585	376,516	37.7	35.9	-3.7 %	5.0 %
Bremen	8	4011000	544,043	541,875	40.4	39.6	0.4 %	2.0 %
Duisburg	8	5112000	487,470	504,105	37.5	36.0	-3.3 %	4.2 %
Essen	8	5113000	565,900	580,410	39.8	38.4	-2.5 %	3.6 %
Gelsenkirchen	8	5513000	257,994	271,573	38.4	36.3	-5.0 %	5.8 %
Herne	8	5916000	154,887	162,016	37.2	35.4	-4.4 %	5.1 %
Koblenz	8	7111000	107,954	108,279	45.3	44.1	-0.3 %	2.7 %
Saarbrücken	8	10041100	176,497	180,652	44.9	43.8	-2.3 %	2.5 %

Table 23: population, floor area per person and their changes between 2011 and 2030

city	cluster id	municipal code	population 2011 [count]	use intensity 2011 [count]	population growth 2011 – 2030 [%]	use intensity change 2011 – 2030 [%]	population 2030 [num]	use intensity 2030 [m2/cap]
Berlin	1	11000000	326,002	38.0	5.8 %	-0.6 %	3,305,221	37.8
Chemnitz	1	14511000	240,543	39.5	-10.6 %	8.5 %	260,974	42.9
Dresden	1	14612000	517,765	35.2	11.8 %	-4.0 %	497,257	33.8
Erfurt	1	16051000	201,952	36.1	-3.4 %	4.5 %	211,020	37.7
Halle	1	15002000	230,494	38.9	-13.1 %	9.9 %	253,275	42.7
Jena	1	16053000	106,428	35.5	-2.8 %	4.2 %	110,852	37.0
Leipzig	1	14713000	510,043	39.3	8.8 %	-2.3 %	498,349	38.4
Magdeburg	1	15003000	228,910	36.6	-6.5 %	6.2 %	243,134	38.9
Potsdam	1	12054000	157,603	35.8	11.2 %	-3.6 %	151,886	34.5
Rostock	1	13003000	201,813	34.7	-7.0 %	6.5 %	214,915	37.0
Bergisch Gladbach	2	5378004	109,026	45.9	-3.7 %	4.7 %	114,104	48.0
Bottrop	2	5512000	117,074	37.1	-6.4 %	6.2 %	124,284	39.4
Hamm	2	5915000	176,474	38.5	-6.7 %	6.3 %	187,636	40.9
Leverkusen	2	5316000	159,373	38.7	-2.5 %	4.0 %	165,732	40.2
Moers	2	5170024	103,831	36.4	-8.3 %	7.2 %	111,322	39.0
Heilbronn	3	8121000	116,716	38.5	2.3 %	1.3 %	118,258	39.0
Ingolstadt	3	9161000	126,076	40.0	10.4 %	-3.2 %	122,064	38.7
Neuss	3	5162024	151,070	40.2	-3.2 %	4.4 %	157,686	42.0
Oldenburg	3	3403000	157,706	44.4	3.5 %	0.7 %	158,737	44.7
Paderborn	3	5774032	143,174	40.8	2.3 %	1.3 %	145,066	41.3
Reutlingen	3	8415061	110,084	38.0	-1.6 %	3.5 %	113,925	39.3
Wolfsburg	3	3103000	120,889	42.9	-10.6 %	8.5 %	131,157	46.5
Bielefeld	4	5711000	327,199	38.2	-5.8 %	5.8 %	346,258	40.4
Bonn	4	5314000	307,530	38.7	4.9 %	-0.1 %	307,147	38.7
Erlangen	4	9562000	104,312	40.3	2.7 %	1.1 %	105,458	40.7
Fürth	4	9563000	116,640	40.4	4.2 %	0.3 %	116,949	40.5
Mainz	4	7315000	201,002	39.1	2.0 %	1.5 %	203,993	39.7
Münster	4	5515000	293,393	40.2	1.4 %	1.8 %	298,737	40.9
Ulm	4	8421000	117,541	37.7	4.0 %	0.4 %	117,983	37.8
Würzburg	4	9663000	124,449	39.5	-4.4 %	5.0 %	130,729	41.5
Augsburg	5	9761000	269,402	38.7	1.2 %	1.9 %	274,609	39.4
Düsseldorf	5	5111000	589,649	39.0	4.5 %	0.1 %	590,227	39.0
Frankfurt am Main	5	6412000	676,533	36.1	7.3 %	-1.5 %	666,664	35.6
Freiburg im Breisgau	5	8311000	214,234	34.6	6.8 %	-1.2 %	211,704	34.2
Hamburg	5	2000000	718,187	35.7	7.2 %	-1.4 %	1,694,077	35.2
Hannover	5	3241001	509,485	40.7	1.5 %	1.8 %	518,483	41.4
Heidelberg	5	8221000	148,415	37.1	3.0 %	0.9 %	149,798	37.4
Karlsruhe	5	8212000	291,995	39.0	3.0 %	0.9 %	294,716	39.4
Kiel	5	1002000	237,667	37.5	3.5 %	0.7 %	239,221	37.7
Köln	5	5315000	013,665	37.4	2.6 %	1.2 %	1,025,367	37.8
Mannheim	5	8222000	291,458	38.9	2.5 %	1.2 %	294,985	39.4
München	5	9162000	364,920	37.0	14.8 %	-5.6 %	1,288,091	34.9
Nürnberg	5	9564000	490,085	38.4	3.0 %	0.9 %	494,653	38.8
Offenbach am Main	5	6413000	114,855	34.5	-2.4 %	3.9 %	119,374	35.9
Regensburg	5	9362000	136,352	42.4	7.2 %	-1.4 %	134,439	41.8
Stuttgart	5	8111000	591,015	35.9	2.8 %	1.0 %	597,180	36.3
Aachen	6	5334002	238,665	37.1	-3.4 %	4.5 %	249,382	38.8
Braunschweig	6	3101000	243,829	41.7	-5.2 %	5.5 %	257,218	44.0
Bremerhaven	6	4012000	108,139	43.5	-3.2 %	4.4 %	112,875	45.4
Darmstadt	6	6411000	145,845	39.8	3.9 %	0.4 %	146,474	40.0
Dortmund	6	5913000	571,403	39.4	-5.2 %	5.5 %	602,780	41.6
Göttingen	6	3152012	116,052	38.6	-8.6 %	7.4 %	124,618	41.4
Hagen	6	5914000	187,333	42.0	-14.7 %	10.8 %	207,515	46.5
Kassel	6	6611000	191,854	39.5	-3.9 %	4.8 %	201,002	41.4
Lübeck	6	1003000	210,679	38.9	-2.8 %	4.2 %	219,437	40.5
Ludwigshafen am Rhein	6	7314000	158,637	39.2	-0.8 %	3.0 %	163,467	40.4
Trier	6	7211000	106,284	41.1	3.8 %	0.5 %	106,802	41.3
Wiesbaden	6	6414000	270,952	38.8	4.2 %	0.3 %	271,669	38.9
Wuppertal	6	5124000	342,570	40.3	-8.8 %	7.5 %	368,238	43.3
Krefeld	7	5114000	221,864	41.3	-5.6 %	5.7 %	234,540	43.7
Mönchengladbach	7	5116000	254,834	39.6	-5.3 %	5.5 %	268,969	41.8
Mülheim an der Ruhr	7	5117000	166,804	43.2	-6.6 %	6.3 %	177,262	45.9
Oberhausen	7	5119000	210,256	36.8	-5.8 %	5.8 %	222,503	38.9
Osnabrück	7	3404000	154,513	41.4	-2.2 %	3.8 %	160,420	43.0
Pforzheim	7	8231000	115,211	38.2	2.0 %	1.5 %	116,925	38.8
Recklinghausen	7	5562032	115,648	40.2	-8.1 %	7.1 %	123,863	43.1
Remscheid	7	5120000	110,132	41.7	-15.1 %	11.0 %	122,242	46.3
Solingen	7	5122000	155,080	37.4	-6.7 %	6.3 %	164,889	39.8
Bochum	8	5911000	362,585	37.7	-10.2 %	8.3 %	392,575	40.8
Bremen	8	4011000	544,043	40.4	0.8 %	2.2 %	555,768	41.3
Duisburg	8	5112000	487,470	37.5	-6.7 %	6.3 %	518,303	39.9
Essen	8	5113000	565,900	39.8	-5.7 %	5.8 %	598,548	42.1
Gelsenkirchen	8	5513000	257,994	38.4	-8.7 %	7.4 %	277,182	41.3
Herne	8	5916000	154,887	37.2	-11.5 %	9.0 %	168,818	40.5
Koblenz	8	7111000	107,954	45.3	-3.4 %	4.5 %	112,802	47.3
Saarbrücken	8	10041100	176,497	44.9	-9.4 %	7.8 %	190,310	48.4

Table 24: share of floor area of single family homes by city

city	cluster id	sfh 1919	sfh 1948	sfh 1978	sfh 1986	sfh 1990	sfh 1995	sfh 2000	sfh 2004	sfh 2008	sfh 2011
Berlin		0.79 %	4.64 %	3.81 %	1.61 %	0.68 %	0.87 %	1.64 %	0.86 %	0.88 %	0.33 %
Chemnitz	1	3.83 %	6.75 %	1.71 %	0.96 %	0.44 %	1.84 %	2.93 %	1.63 %	1.18 %	0.47 %
Dresden	1	4.12 %	5.56 %	1.38 %	0.67 %	0.30 %	1.03 %	1.90 %	1.04 %	1.14 %	0.48 %
Erfurt	1	4.05 %	5.01 %	3.40 %	1.50 %	0.63 %	2.11 %	3.59 %	2.27 %	1.75 %	0.80 %
Halle	1	2.66 %	5.63 %	2.11 %	0.56 %	0.26 %	0.65 %	1.77 %	1.43 %	1.27 %	0.44 %
Jena	1	4.58 %	9.35 %	2.42 %	0.97 %	0.39 %	1.87 %	2.69 %	1.79 %	1.66 %	1.04 %
Leipzig	1	1.39 %	5.47 %	1.57 %	0.70 %	0.30 %	1.02 %	1.98 %	1.25 %	1.08 %	0.46 %
Magdeburg	1	2.21 %	7.11 %	2.57 %	0.92 %	0.47 %	1.82 %	3.40 %	2.35 %	1.76 %	0.55 %
Potsdam	1	3.29 %	5.95 %	2.29 %	0.94 %	0.43 %	1.57 %	3.38 %	2.28 %	2.22 %	1.02 %
Rostock	1	1.08 %	3.24 %	1.80 %	0.35 %	0.22 %	0.56 %	2.66 %	2.47 %	1.13 %	0.41 %
Bergisch Gladbach	1	3.87 %	5.36 %	2.39 %	4.32 %	1.78 %	2.06 %	2.30 %	1.90 %	1.41 %	0.63 %
Bottrop	2	8.91 %	4.34 %	2.34 %	2.38 %	1.82 %	1.73 %	1.43 %	0.83 %	1.15 %	0.66 %
Hamm	2	7.46 %	6.99 %	6.59 %	3.69 %	1.55 %	2.13 %	2.48 %	2.26 %	1.70 %	0.70 %
Leverkusen	2	3.74 %	4.78 %	3.74 %	2.18 %	1.16 %	1.27 %	1.28 %	1.15 %	1.20 %	0.64 %
Moers	2	4.49 %	3.51 %	8.30 %	2.52 %	2.03 %	2.41 %	2.62 %	2.47 %	1.46 %	0.33 %
Heilbronn	2	3.62 %	7.04 %	6.61 %	3.19 %	1.11 %	1.04 %	1.14 %	1.02 %	0.89 %	0.20 %
Ingolstadt	3	1.15 %	2.95 %	8.99 %	6.28 %	3.03 %	2.78 %	3.71 %	2.66 %	2.44 %	1.09 %
Neuss	3	1.56 %	2.53 %	2.81 %	2.44 %	1.04 %	1.61 %	1.77 %	1.19 %	0.94 %	0.72 %
Oldenburg	3	5.06 %	5.93 %	1.14 %	6.18 %	2.69 %	4.05 %	5.00 %	2.44 %	2.07 %	0.99 %
Paderborn	3	1.64 %	3.04 %	6.96 %	4.80 %	2.92 %	3.27 %	3.88 %	2.61 %	1.89 %	0.96 %
Reutlingen	3	5.42 %	5.15 %	6.75 %	4.36 %	1.93 %	1.95 %	1.82 %	1.51 %	1.28 %	0.48 %
Wolfsburg	3	2.36 %	1.13 %	9.29 %	4.53 %	2.31 %	2.15 %	3.39 %	3.38 %	3.30 %	1.37 %
Bielefeld	3	3.66 %	5.58 %	3.78 %	3.42 %	1.30 %	1.50 %	1.93 %	1.75 %	1.51 %	0.71 %
Bonn	4	2.51 %	2.59 %	1.37 %	2.13 %	0.97 %	1.11 %	1.12 %	0.77 %	0.84 %	0.44 %
Erlangen	4	1.79 %	3.51 %	4.23 %	2.86 %	1.14 %	1.45 %	1.65 %	1.49 %	1.40 %	0.58 %
Fürth	4	1.80 %	3.28 %	0.82 %	3.46 %	1.46 %	1.97 %	1.64 %	0.93 %	1.05 %	0.49 %
Mainz	4	3.96 %	2.93 %	1.26 %	2.73 %	0.76 %	0.72 %	0.96 %	0.57 %	0.83 %	0.48 %
Münster	4	0.88 %	2.58 %	4.15 %	3.32 %	1.41 %	1.73 %	2.17 %	1.49 %	1.85 %	0.95 %
Ulm	4	2.17 %	3.57 %	0.41 %	3.04 %	1.59 %	1.81 %	1.74 %	1.29 %	1.29 %	0.61 %
Würzburg	4	1.14 %	2.99 %	0.86 %	3.48 %	1.42 %	1.36 %	1.16 %	0.63 %	0.62 %	0.36 %
Augsburg	4	1.60 %	3.25 %	8.62 %	1.58 %	0.77 %	0.90 %	0.83 %	0.67 %	0.83 %	0.33 %
Düsseldorf	5	0.75 %	2.33 %	4.90 %	0.75 %	0.42 %	0.41 %	0.47 %	0.42 %	0.40 %	0.20 %
Frankfurt am Main	5	2.63 %	2.26 %	4.53 %	0.64 %	0.26 %	0.24 %	0.34 %	0.29 %	0.34 %	0.08 %
Freiburg im Breisgau	5	1.92 %	2.58 %	7.05 %	1.54 %	0.80 %	0.92 %	0.84 %	0.65 %	0.49 %	0.20 %
Hamburg	5	2.14 %	4.43 %	8.93 %	2.28 %	1.06 %	1.17 %	1.31 %	0.84 %	0.88 %	0.44 %
Hannover	5	0.88 %	2.74 %	7.05 %	1.15 %	0.58 %	0.66 %	0.78 %	0.65 %	0.64 %	0.23 %
Heidelberg	5	2.88 %	3.21 %	7.34 %	2.15 %	0.58 %	0.63 %	0.56 %	0.35 %	0.44 %	0.26 %
Karlsruhe	5	2.24 %	3.59 %	8.82 %	1.83 %	0.60 %	0.86 %	0.81 %	0.56 %	0.49 %	0.29 %
Kiel	5	1.40 %	5.74 %	8.96 %	2.27 %	0.70 %	0.69 %	0.80 %	0.92 %	0.82 %	0.41 %
Köln	5	1.21 %	2.21 %	6.65 %	1.14 %	0.49 %	0.57 %	0.57 %	0.56 %	0.54 %	0.33 %
Mannheim	5	1.82 %	4.41 %	5.85 %	1.85 %	0.61 %	0.70 %	0.63 %	0.50 %	0.38 %	0.15 %
München	5	0.57 %	2.60 %	5.95 %	1.65 %	0.61 %	0.56 %	0.60 %	0.59 %	0.60 %	0.35 %
Nürnberg	5	1.00 %	2.97 %	8.07 %	1.66 %	0.88 %	0.83 %	0.76 %	0.62 %	0.57 %	0.24 %
Offenbach am Main	5	2.68 %	4.56 %	8.12 %	1.41 %	0.30 %	0.39 %	0.52 %	0.32 %	0.31 %	0.07 %
Regensburg	5	1.53 %	3.39 %	7.83 %	2.06 %	0.83 %	1.50 %	1.19 %	0.93 %	1.19 %	0.56 %
Stuttgart	5	2.66 %	6.40 %	5.77 %	0.96 %	0.44 %	0.39 %	0.43 %	0.39 %	0.44 %	0.21 %
Aachen	5	1.79 %	2.68 %	0.85 %	2.00 %	1.05 %	0.93 %	1.06 %	0.78 %	0.65 %	0.40 %
Braunschweig	6	2.13 %	5.29 %	1.72 %	1.83 %	0.67 %	0.95 %	1.36 %	1.74 %	1.70 %	0.51 %
Bremerhaven	6	2.34 %	5.89 %	5.30 %	3.12 %	0.68 %	1.12 %	2.32 %	2.04 %	0.91 %	0.23 %
Darmstadt	6	4.12 %	4.67 %	1.78 %	1.87 %	0.75 %	0.85 %	0.81 %	0.65 %	0.70 %	0.21 %
Dortmund	6	3.36 %	3.05 %	9.39 %	1.45 %	0.69 %	0.79 %	1.14 %	1.22 %	1.05 %	0.47 %
Göttingen	6	2.84 %	2.95 %	0.89 %	2.03 %	0.68 %	0.68 %	0.74 %	0.39 %	0.57 %	0.39 %
Hagen	6	2.74 %	4.33 %	0.91 %	1.90 %	1.06 %	1.05 %	1.12 %	0.74 %	0.81 %	0.34 %
Kassel	6	1.95 %	5.71 %	2.47 %	2.29 %	0.85 %	1.01 %	1.06 %	0.76 %	0.73 %	0.22 %
Lübeck	6	4.39 %	6.73 %	3.23 %	1.94 %	0.82 %	1.17 %	1.27 %	0.88 %	0.98 %	0.44 %
Ludwigshafen am Rhein	6	4.58 %	6.78 %	0.56 %	1.19 %	0.71 %	0.79 %	0.77 %	0.80 %	0.69 %	0.42 %
Trier	6	2.23 %	2.86 %	0.28 %	2.21 %	0.66 %	1.02 %	1.01 %	0.81 %	1.11 %	0.55 %
Wiesbaden	6	3.65 %	2.91 %	0.38 %	2.01 %	0.78 %	0.81 %	0.73 %	0.55 %	0.59 %	0.20 %
Wuppertal	6	2.96 %	3.57 %	9.18 %	1.61 %	0.71 %	0.71 %	0.81 %	0.53 %	0.55 %	0.33 %
Krefeld	6	2.12 %	3.85 %	1.92 %	3.15 %	1.69 %	1.64 %	1.48 %	1.50 %	0.98 %	0.43 %
Mönchengladbach	7	3.93 %	3.07 %	0.42 %	2.68 %	1.50 %	1.78 %	1.63 %	1.21 %	0.86 %	0.42 %
Mülheim an der Ruhr	7	4.93 %	4.07 %	1.30 %	2.13 %	0.77 %	1.03 %	1.21 %	0.94 %	0.64 %	0.36 %
Oberhausen	7	5.17 %	3.78 %	9.63 %	1.65 %	0.63 %	0.94 %	0.94 %	0.91 %	0.72 %	0.36 %
Osnabrück	7	1.90 %	4.50 %	5.04 %	3.61 %	1.70 %	1.70 %	1.60 %	1.41 %	1.17 %	0.50 %
Pforzheim	7	1.76 %	4.16 %	2.80 %	2.80 %	1.06 %	1.05 %	0.82 %	0.71 %	0.93 %	0.63 %
Recklinghausen	7	4.32 %	3.41 %	1.28 %	2.19 %	2.03 %	1.70 %	1.41 %	1.16 %	1.08 %	0.64 %
Remscheid	7	7.26 %	5.03 %	2.26 %	2.07 %	1.02 %	1.66 %	1.36 %	1.16 %	0.93 %	0.25 %
Solingen	7	0.11 %	4.05 %	2.70 %	2.50 %	1.11 %	1.32 %	1.53 %	1.33 %	1.06 %	0.43 %
Bochum	7	3.26 %	3.41 %	8.79 %	1.52 %	0.73 %	0.71 %	0.88 %	0.58 %	0.60 %	0.30 %
Bremen	8	3.42 %	5.36 %	9.71 %	2.29 %	0.83 %	1.04 %	1.28 %	0.96 %	0.77 %	0.29 %
Duisburg	8	3.40 %	3.99 %	7.25 %	0.96 %	0.90 %	1.07 %	1.06 %	0.74 %	0.66 %	0.37 %
Essen	8	3.68 %	3.95 %	7.24 %	0.90 %	0.47 %	0.43 %	0.52 %	0.52 %	0.53 %	0.31 %
Gelsenkirchen	8	4.00 %	2.80 %	4.55 %	0.84 %	0.74 %	0.56 %	0.59 %	0.53 %	0.49 %	0.19 %
Herne	8	5.24 %	3.61 %	6.76 %	1.55 %	0.64 %	0.73 %	0.65 %	0.66 %	0.43 %	0.16 %
Koblenz	8	4.02 %	3.40 %	2.29 %	2.41 %	1.04 %	1.16 %	1.23 %	0.95 %	1.17 %	0.35 %
Saarbrücken	8	4.68 %	7.26 %	4.65 %	1.83 %	0.73 %	0.86 %	0.81 %	0.61 %	0.56 %	0.24 %

Table 25: share of floor area of big multi-family homes by city

city	cluster id	bmh 1919	bmh 1948	bmh 1978	bmh 1986	bmh 1990	bmh 1995	bmh 2000	bmh 2004	bmh 2008	bmh 2011
Berlin		4.26 %	1.85 %	5.77 %	3.96 %	3.12 %	1.49 %	2.85 %	0.27 %	0.24 %	0.17 %
Chemnitz	1	7.75 %	2.25 %	6.94 %	2.91 %	1.07 %	1.65 %	4.11 %	0.41 %	0.37 %	0.00 %
Dresden	1	5.74 %	1.67 %	9.19 %	4.59 %	2.02 %	4.20 %	5.79 %	0.25 %	0.26 %	0.30 %
Erfurt	1	2.47 %	1.00 %	3.17 %	2.74 %	2.56 %	1.64 %	2.50 %	0.48 %	0.31 %	0.10 %
Halle	1	4.10 %	1.06 %	0.51 %	1.84 %	1.84 %	1.21 %	3.25 %	0.23 %	0.38 %	0.06 %
Jena	1	1.13 %	0.94 %	8.51 %	4.01 %	3.24 %	1.43 %	2.83 %	0.64 %	0.60 %	0.20 %
Leipzig	1	0.75 %	2.72 %	5.28 %	4.17 %	2.51 %	2.70 %	6.79 %	0.42 %	0.45 %	0.16 %
Magdeburg	1	5.29 %	1.57 %	9.21 %	2.63 %	1.69 %	1.94 %	3.40 %	0.25 %	0.49 %	0.06 %
Potsdam	1	3.05 %	0.68 %	6.69 %	3.90 %	1.83 %	2.46 %	4.24 %	0.85 %	1.61 %	0.23 %
Rostock	1	0.35 %	0.47 %	2.16 %	6.84 %	3.70 %	1.13 %	1.23 %	1.08 %	0.40 %	0.45 %
Bergisch Gladbach	1	0.00 %	0.00 %	5.36 %	1.21 %	0.00 %	0.45 %	0.38 %	0.17 %	0.38 %	0.29 %
Bottrop	2	0.00 %	0.08 %	2.02 %	0.56 %	0.00 %	0.28 %	0.56 %	0.30 %	0.52 %	0.00 %
Hamm	2	0.00 %	0.00 %	4.51 %	1.04 %	0.00 %	0.29 %	0.63 %	0.44 %	0.36 %	0.08 %
Leverkusen	2	0.00 %	0.00 %	6.97 %	0.86 %	0.37 %	0.57 %	0.53 %	0.00 %	0.44 %	0.09 %
Moers	2	0.00 %	0.00 %	4.08 %	0.57 %	0.15 %	0.15 %	0.28 %	0.00 %	0.14 %	0.00 %
Heilbronn	2	0.00 %	0.08 %	6.00 %	1.36 %	0.72 %	1.80 %	0.76 %	0.50 %	0.25 %	0.42 %
Ingolstadt	3	0.14 %	0.14 %	7.21 %	1.12 %	0.57 %	2.07 %	0.87 %	0.72 %	0.72 %	0.38 %
Neuss	3	0.06 %	0.00 %	6.97 %	1.07 %	0.31 %	1.91 %	1.07 %	0.32 %	0.71 %	0.10 %
Oldenburg	3	0.05 %	0.19 %	3.57 %	0.88 %	0.08 %	1.70 %	0.54 %	0.31 %	0.23 %	0.08 %
Paderborn	3	0.12 %	0.21 %	3.40 %	0.86 %	0.21 %	1.52 %	0.60 %	0.30 %	0.50 %	0.20 %
Reutlingen	3	0.08 %	0.00 %	4.45 %	0.49 %	0.28 %	2.18 %	0.27 %	0.58 %	0.27 %	0.27 %
Wolfsburg	3	0.07 %	0.00 %	9.54 %	0.39 %	0.12 %	1.09 %	0.45 %	0.23 %	0.00 %	0.00 %
Bielefeld	3	0.19 %	0.13 %	4.93 %	1.06 %	0.21 %	1.28 %	1.03 %	0.42 %	0.37 %	0.15 %
Bonn	4	0.34 %	0.25 %	7.66 %	1.94 %	0.92 %	2.11 %	1.25 %	0.44 %	0.66 %	0.25 %
Erlangen	4	0.50 %	0.38 %	8.98 %	2.01 %	0.44 %	3.19 %	1.01 %	0.46 %	1.19 %	0.00 %
Fürth	4	2.14 %	0.08 %	8.23 %	1.74 %	0.41 %	3.85 %	0.69 %	0.69 %	0.39 %	0.00 %
Mainz	4	1.02 %	0.57 %	4.70 %	2.30 %	1.26 %	1.28 %	2.17 %	0.77 %	0.47 %	0.95 %
Münster	4	0.20 %	0.16 %	7.62 %	1.88 %	0.32 %	1.58 %	1.09 %	0.59 %	0.54 %	0.72 %
Ulm	4	0.15 %	0.16 %	6.98 %	3.21 %	1.07 %	2.68 %	1.42 %	0.42 %	0.96 %	0.50 %
Würzburg	4	0.46 %	0.61 %	6.06 %	1.38 %	0.69 %	3.24 %	2.05 %	0.36 %	0.50 %	0.32 %
Augsburg	4	0.98 %	0.49 %	1.66 %	2.59 %	2.65 %	4.60 %	1.84 %	0.34 %	0.78 %	0.34 %
Düsseldorf	5	0.76 %	1.29 %	7.84 %	2.02 %	0.48 %	1.73 %	1.88 %	0.36 %	0.39 %	0.39 %
Frankfurt am Main	5	1.51 %	0.53 %	6.09 %	1.24 %	0.77 %	1.52 %	1.57 %	1.33 %	1.47 %	0.65 %
Freiburg im Breisgau	5	0.46 %	0.56 %	1.79 %	3.11 %	1.16 %	3.02 %	3.86 %	1.39 %	1.66 %	0.91 %
Hamburg	5	3.46 %	1.47 %	3.50 %	1.33 %	0.50 %	0.94 %	1.16 %	0.52 %	0.57 %	0.40 %
Hannover	5	2.32 %	1.64 %	5.08 %	0.95 %	0.34 %	1.44 %	1.42 %	0.32 %	0.27 %	0.15 %
Heidelberg	5	1.22 %	0.84 %	0.04 %	3.28 %	1.26 %	2.60 %	1.95 %	0.59 %	1.11 %	0.52 %
Karlsruhe	5	1.81 %	0.38 %	2.21 %	1.71 %	1.33 %	2.44 %	1.23 %	0.32 %	0.72 %	0.72 %
Kiel	5	2.17 %	1.23 %	1.31 %	1.17 %	0.35 %	1.28 %	1.73 %	0.27 %	0.37 %	0.06 %
Köln	5	0.72 %	0.77 %	3.59 %	1.60 %	0.50 %	1.33 %	1.98 %	1.07 %	0.86 %	0.73 %
Mannheim	5	1.64 %	0.83 %	4.26 %	1.60 %	0.99 %	1.78 %	1.53 %	0.46 %	0.22 %	0.38 %
München	5	4.77 %	1.13 %	5.21 %	3.49 %	2.29 %	2.46 %	2.20 %	1.66 %	1.78 %	0.64 %
Nürnberg	5	1.04 %	0.47 %	6.42 %	2.13 %	0.81 %	3.29 %	1.19 %	0.55 %	0.61 %	0.21 %
Offenbach am Main	5	1.38 %	0.81 %	0.73 %	1.11 %	0.61 %	1.78 %	1.76 %	0.43 %	0.14 %	0.14 %
Regensburg	5	1.78 %	0.27 %	9.75 %	2.09 %	1.29 %	3.70 %	1.81 %	1.48 %	2.21 %	0.87 %
Stuttgart	5	0.92 %	0.38 %	9.26 %	1.87 %	0.71 %	1.86 %	1.42 %	0.53 %	0.90 %	0.29 %
Aachen	5	0.86 %	0.40 %	9.31 %	2.36 %	0.26 %	1.95 %	1.06 %	0.12 %	0.06 %	0.06 %
Braunschweig	6	1.01 %	0.75 %	0.73 %	1.29 %	0.00 %	0.82 %	0.61 %	0.12 %	0.31 %	0.00 %
Bremerhaven	6	0.88 %	0.41 %	0.13 %	0.92 %	0.13 %	0.31 %	0.33 %	0.00 %	0.12 %	0.12 %
Darmstadt	6	0.25 %	0.67 %	9.06 %	1.47 %	0.94 %	1.66 %	0.74 %	0.32 %	0.95 %	0.32 %
Dortmund	6	0.39 %	0.27 %	8.20 %	1.26 %	0.14 %	0.79 %	0.50 %	0.23 %	0.30 %	0.18 %
Göttingen	6	0.86 %	0.29 %	9.58 %	2.10 %	1.43 %	2.91 %	0.63 %	0.25 %	0.13 %	0.13 %
Hagen	6	0.26 %	0.15 %	9.35 %	0.99 %	0.09 %	0.46 %	0.59 %	0.08 %	0.08 %	0.08 %
Kassel	6	1.76 %	0.63 %	9.08 %	0.27 %	0.45 %	1.34 %	0.42 %	0.24 %	0.08 %	0.00 %
Lübeck	6	0.61 %	0.18 %	7.74 %	0.96 %	0.39 %	1.11 %	1.38 %	0.06 %	0.50 %	0.37 %
Ludwigshafen am Rhein	6	0.11 %	0.18 %	1.66 %	1.59 %	0.78 %	1.56 %	1.46 %	0.57 %	0.13 %	0.41 %
Trier	6	0.64 %	0.22 %	5.56 %	1.95 %	0.85 %	1.61 %	1.20 %	0.27 %	0.13 %	0.58 %
Wiesbaden	6	4.46 %	0.55 %	0.40 %	1.26 %	0.53 %	1.06 %	1.49 %	0.17 %	0.23 %	0.06 %
Wuppertal	6	0.43 %	0.16 %	0.34 %	1.42 %	0.25 %	0.86 %	0.79 %	0.13 %	0.20 %	0.09 %
Krefeld	6	0.19 %	0.08 %	5.52 %	1.18 %	0.16 %	0.63 %	0.63 %	0.13 %	0.06 %	0.00 %
Mönchengladbach	7	0.13 %	0.03 %	5.63 %	0.65 %	0.25 %	0.62 %	0.45 %	0.22 %	0.24 %	0.05 %
Mülheim an der Ruhr	7	0.05 %	0.13 %	6.11 %	0.86 %	0.47 %	0.50 %	0.18 %	0.38 %	0.18 %	0.00 %
Oberhausen	7	0.13 %	0.00 %	4.13 %	0.86 %	0.15 %	0.33 %	0.91 %	0.26 %	0.36 %	0.17 %
Osnabrück	7	0.29 %	0.00 %	3.66 %	1.08 %	0.19 %	0.97 %	1.06 %	0.00 %	0.00 %	0.09 %
Pforzheim	7	0.00 %	0.40 %	3.87 %	1.61 %	0.96 %	2.70 %	0.94 %	0.64 %	0.26 %	0.00 %
Recklinghausen	7	0.15 %	0.08 %	2.02 %	0.34 %	0.13 %	0.27 %	1.00 %	0.12 %	0.37 %	0.29 %
Remscheid	7	0.16 %	0.17 %	5.99 %	0.45 %	0.00 %	0.71 %	0.97 %	0.13 %	0.40 %	0.00 %
Solingen	7	0.22 %	0.00 %	3.83 %	0.79 %	0.23 %	0.58 %	0.39 %	0.27 %	0.09 %	0.27 %
Bochum	7	0.08 %	0.08 %	6.12 %	0.87 %	0.20 %	1.07 %	0.98 %	0.14 %	0.23 %	0.09 %
Bremen	8	0.10 %	0.06 %	7.26 %	0.65 %	0.17 %	1.04 %	0.92 %	0.32 %	0.48 %	0.16 %
Duisburg	8	0.10 %	0.14 %	6.27 %	1.01 %	0.22 %	0.42 %	0.56 %	0.10 %	0.16 %	0.10 %
Essen	8	0.10 %	0.25 %	7.72 %	0.64 %	0.17 %	0.44 %	0.33 %	0.27 %	0.14 %	0.16 %
Gelsenkirchen	8	0.15 %	0.40 %	6.48 %	0.99 %	0.27 %	0.49 %	0.25 %	0.37 %	0.12 %	0.17 %
Herne	8	0.47 %	0.06 %	5.57 %	0.58 %	0.11 %	0.47 %	0.44 %	0.20 %	0.44 %	0.10 %
Koblenz	8	0.43 %	0.27 %	6.75 %	0.55 %	0.59 %	0.68 %	0.97 %	0.51 %	0.25 %	0.00 %
Saarbrücken	8	0.23 %	0.19 %	7.71 %	1.60 %	0.58 %	1.53 %	1.23 %	0.00 %	0.08 %	0.08 %

Table 26: share of floor area of small multi-family homes by city

city	cluster id	smh 1919	smh 1948	smh 1978	smh 1986	smh 1990	smh 1995	smh 2000	smh 2004	smh 2008	smh 2011
Berlin		1.78 %	2.37 %	1.77 %	0.34 %	0.15 %	0.39 %	0.47 %	0.09 %	0.06 %	0.04 %
Chemnitz	1	4.22 %	4.91 %	1.48 %	0.25 %	0.08 %	0.55 %	1.03 %	0.24 %	0.13 %	0.03 %
Dresden	1	4.87 %	4.42 %	0.69 %	0.04 %	0.08 %	0.60 %	1.12 %	0.17 %	0.15 %	0.10 %
Erfurt	1	4.99 %	3.97 %	1.63 %	0.22 %	0.01 %	0.92 %	1.15 %	0.35 %	0.20 %	0.08 %
Halle	1	4.62 %	4.52 %	1.47 %	0.23 %	0.04 %	0.24 %	0.64 %	0.44 %	0.28 %	0.10 %
Jena	1	8.30 %	6.28 %	0.87 %	0.05 %	0.05 %	0.54 %	0.94 %	0.32 %	0.33 %	0.25 %
Leipzig	1	2.81 %	2.52 %	0.60 %	0.05 %	0.02 %	0.35 %	0.59 %	0.08 %	0.10 %	0.04 %
Magdeburg	1	2.60 %	7.42 %	1.42 %	0.11 %	0.06 %	0.71 %	0.94 %	0.09 %	0.13 %	0.05 %
Potsdam	1	4.82 %	3.59 %	1.63 %	0.27 %	0.22 %	0.70 %	1.37 %	0.36 %	0.39 %	0.30 %
Rostock	1	3.11 %	3.48 %	1.17 %	0.17 %	0.05 %	0.24 %	1.00 %	0.39 %	0.19 %	0.06 %
Bergisch Gladbach	1	1.26 %	1.19 %	2.15 %	2.25 %	0.62 %	1.44 %	1.43 %	0.86 %	0.40 %	0.20 %
Bottrop	2	2.86 %	2.72 %	9.66 %	2.91 %	1.57 %	1.78 %	1.56 %	0.89 %	0.49 %	0.19 %
Hamm	2	3.81 %	4.29 %	3.15 %	1.41 %	0.37 %	1.27 %	0.87 %	0.38 %	0.14 %	0.04 %
Leverkusen	2	2.88 %	3.68 %	2.86 %	1.59 %	0.50 %	1.70 %	1.02 %	0.44 %	0.29 %	0.16 %
Moers	2	1.98 %	2.26 %	2.71 %	2.31 %	0.38 %	1.26 %	1.36 %	0.68 %	0.41 %	0.05 %
Heilbronn	2	2.52 %	3.96 %	5.66 %	1.79 %	0.81 %	1.25 %	0.91 %	0.49 %	0.36 %	0.09 %
Ingolstadt	3	1.36 %	1.17 %	6.23 %	1.23 %	0.95 %	2.22 %	1.70 %	1.08 %	1.06 %	0.50 %
Neuss	3	3.00 %	2.71 %	1.19 %	1.56 %	0.67 %	0.97 %	0.79 %	0.28 %	0.29 %	0.08 %
Oldenburg	3	3.60 %	1.91 %	7.85 %	1.78 %	0.46 %	1.54 %	1.05 %	0.19 %	0.37 %	0.22 %
Paderborn	3	1.30 %	2.70 %	3.39 %	2.70 %	1.23 %	2.20 %	2.01 %	0.79 %	0.58 %	0.18 %
Reutlingen	3	3.69 %	2.57 %	7.76 %	2.20 %	0.64 %	1.86 %	0.90 %	0.38 %	0.47 %	0.29 %
Wolfsburg	3	0.87 %	1.47 %	0.61 %	1.04 %	0.56 %	1.05 %	0.38 %	0.34 %	0.33 %	0.15 %
Bielefeld	3	4.45 %	4.96 %	5.13 %	1.90 %	0.43 %	1.22 %	1.11 %	0.44 %	0.30 %	0.20 %
Bonn	4	6.58 %	2.73 %	3.82 %	2.18 %	0.44 %	1.18 %	1.06 %	0.33 %	0.34 %	0.23 %
Erlangen	4	3.39 %	1.64 %	0.52 %	1.51 %	0.53 %	1.14 %	0.67 %	0.31 %	0.19 %	0.19 %
Fürth	4	4.75 %	2.17 %	6.54 %	1.05 %	0.42 %	1.10 %	0.51 %	0.41 %	0.54 %	0.41 %
Mainz	4	2.64 %	2.03 %	7.19 %	2.13 %	0.78 %	1.02 %	1.06 %	0.41 %	0.48 %	0.19 %
Münster	4	1.67 %	3.61 %	2.41 %	1.73 %	0.46 %	0.83 %	0.99 %	0.36 %	0.30 %	0.20 %
Ulm	4	4.29 %	3.71 %	9.26 %	1.30 %	0.44 %	1.15 %	1.09 %	0.33 %	0.27 %	0.13 %
Würzburg	4	1.03 %	2.20 %	9.60 %	2.09 %	0.73 %	0.85 %	0.56 %	0.24 %	0.22 %	0.09 %
Augsburg	4	3.22 %	3.03 %	6.85 %	1.04 %	0.42 %	0.52 %	0.39 %	0.24 %	0.18 %	0.12 %
Düsseldorf	5	3.71 %	3.33 %	9.41 %	1.69 %	0.30 %	0.53 %	0.45 %	0.25 %	0.16 %	0.13 %
Frankfurt am Main	5	6.92 %	3.85 %	8.19 %	0.93 %	0.39 %	0.62 %	0.60 %	0.37 %	0.34 %	0.13 %
Freiburg im Breisgau	5	7.06 %	2.69 %	9.48 %	1.95 %	0.72 %	0.98 %	0.96 %	0.73 %	0.42 %	0.22 %
Hamburg	5	2.28 %	1.50 %	7.25 %	0.85 %	0.17 %	0.47 %	0.57 %	0.28 %	0.25 %	0.09 %
Hannover	5	2.29 %	2.05 %	7.57 %	0.65 %	0.24 %	0.39 %	0.30 %	0.10 %	0.07 %	0.05 %
Heidelberg	5	8.79 %	4.46 %	1.38 %	1.98 %	0.52 %	0.93 %	0.75 %	0.33 %	0.42 %	0.31 %
Karlsruhe	5	5.16 %	3.17 %	9.91 %	1.18 %	0.43 %	0.72 %	0.54 %	0.24 %	0.26 %	0.10 %
Kiel	5	2.55 %	4.39 %	5.97 %	0.74 %	0.26 %	0.20 %	0.24 %	0.03 %	0.10 %	0.04 %
Köln	5	2.81 %	3.02 %	1.52 %	1.37 %	0.37 %	0.78 %	0.77 %	0.46 %	0.31 %	0.20 %
Mannheim	5	3.17 %	4.09 %	9.64 %	1.75 %	0.56 %	0.75 %	0.58 %	0.23 %	0.19 %	0.05 %
München	5	1.00 %	1.40 %	3.92 %	0.97 %	0.42 %	0.69 %	0.70 %	0.47 %	0.45 %	0.21 %
Nürnberg	5	2.54 %	2.63 %	6.52 %	0.82 %	0.29 %	0.53 %	0.29 %	0.18 %	0.26 %	0.07 %
Offenbach am Main	5	5.44 %	3.19 %	9.78 %	1.13 %	0.57 %	0.73 %	0.48 %	0.35 %	0.19 %	0.09 %
Regensburg	5	3.68 %	2.66 %	6.99 %	1.36 %	0.55 %	1.53 %	0.87 %	0.37 %	0.40 %	0.39 %
Stuttgart	5	6.57 %	6.96 %	4.17 %	1.56 %	0.66 %	0.89 %	0.55 %	0.44 %	0.44 %	0.19 %
Aachen	5	5.65 %	2.51 %	1.21 %	1.99 %	0.35 %	0.83 %	0.81 %	0.36 %	0.23 %	0.12 %
Braunschweig	6	4.11 %	4.09 %	7.91 %	0.72 %	0.26 %	0.42 %	0.35 %	0.16 %	0.24 %	0.06 %
Bremerhaven	6	2.84 %	2.69 %	7.30 %	0.45 %	0.02 %	0.26 %	0.45 %	0.23 %	0.08 %	0.08 %
Darmstadt	6	5.65 %	2.22 %	1.90 %	1.57 %	0.62 %	0.77 %	0.76 %	0.37 %	0.34 %	0.12 %
Dortmund	6	5.56 %	3.94 %	6.05 %	1.74 %	0.28 %	0.84 %	0.75 %	0.44 %	0.15 %	0.09 %
Göttingen	6	6.69 %	3.91 %	1.92 %	1.67 %	0.40 %	0.75 %	0.35 %	0.15 %	0.19 %	0.04 %
Hagen	6	5.66 %	5.32 %	4.90 %	1.39 %	0.27 %	0.69 %	0.82 %	0.34 %	0.14 %	0.08 %
Kassel	6	2.49 %	5.17 %	4.38 %	1.14 %	0.34 %	1.32 %	0.96 %	0.21 %	0.17 %	0.07 %
Lübeck	6	8.04 %	2.82 %	6.53 %	0.62 %	0.25 %	0.36 %	0.45 %	0.25 %	0.14 %	0.04 %
Ludwigshafen am Rhein	6	2.90 %	4.31 %	8.49 %	0.89 %	0.31 %	0.93 %	0.69 %	0.36 %	0.27 %	0.15 %
Trier	6	6.40 %	5.27 %	3.80 %	2.20 %	0.62 %	1.01 %	0.87 %	0.30 %	0.44 %	0.42 %
Wiesbaden	6	5.98 %	2.56 %	8.41 %	1.39 %	0.47 %	0.88 %	0.87 %	0.40 %	0.33 %	0.07 %
Wuppertal	6	9.16 %	3.97 %	1.93 %	0.86 %	0.22 %	0.89 %	0.38 %	0.24 %	0.12 %	0.11 %
Krefeld	6	6.16 %	4.88 %	2.12 %	1.76 %	0.36 %	0.89 %	0.79 %	0.27 %	0.07 %	0.05 %
Mönchengladbach	7	4.83 %	3.58 %	4.27 %	2.91 %	0.59 %	1.16 %	0.90 %	0.27 %	0.15 %	0.08 %
Mülheim an der Ruhr	7	7.93 %	4.12 %	7.22 %	2.11 %	0.29 %	0.71 %	0.75 %	0.27 %	0.11 %	0.14 %
Oberhausen	7	6.89 %	4.53 %	1.15 %	2.28 %	0.54 %	1.13 %	1.10 %	0.36 %	0.17 %	0.05 %
Osnabrück	7	4.09 %	6.42 %	4.82 %	1.58 %	0.44 %	1.31 %	0.88 %	0.29 %	0.32 %	0.05 %
Pforzheim	7	3.68 %	2.24 %	1.07 %	1.46 %	0.68 %	1.55 %	0.66 %	0.27 %	0.33 %	0.22 %
Recklinghausen	7	6.79 %	4.09 %	9.43 %	3.19 %	0.56 %	1.11 %	0.70 %	0.35 %	0.12 %	0.08 %
Remscheid	7	6.55 %	4.04 %	4.59 %	1.00 %	0.47 %	0.54 %	0.70 %	0.25 %	0.22 %	0.02 %
Solingen	7	9.86 %	7.07 %	2.06 %	1.51 %	0.21 %	0.99 %	1.04 %	0.46 %	0.25 %	0.04 %
Bochum	7	6.48 %	4.84 %	0.30 %	1.56 %	0.40 %	0.62 %	0.60 %	0.27 %	0.16 %	0.08 %
Bremen	8	3.65 %	3.10 %	2.98 %	0.87 %	0.24 %	0.51 %	0.35 %	0.13 %	0.11 %	0.03 %
Duisburg	8	6.19 %	5.56 %	8.11 %	1.32 %	0.24 %	0.54 %	0.81 %	0.49 %	0.15 %	0.05 %
Essen	8	6.56 %	5.88 %	8.98 %	1.66 %	0.31 %	0.48 %	0.50 %	0.29 %	0.17 %	0.08 %
Gelsenkirchen	8	8.50 %	5.29 %	0.19 %	1.23 %	0.51 %	0.40 %	0.48 %	0.27 %	0.15 %	0.09 %
Herne	8	9.24 %	5.22 %	7.96 %	1.25 %	0.33 %	0.60 %	0.54 %	0.29 %	0.20 %	0.10 %
Koblenz	8	4.94 %	3.09 %	6.98 %	2.51 %	0.46 %	1.20 %	1.43 %	0.43 %	0.28 %	0.19 %
Saarbrücken	8	4.37 %	5.53 %	4.56 %	1.22 %	0.26 %	0.52 %	0.59 %	0.24 %	0.10 %	0.07 %

Table 27: share of floor area of medium multi-family homes by city

city	cluster id	mmh 1919	mmh 1948	mmh 1978	mmh 1986	mmh 1990	mmh 1995	mmh 2000	mmh 2004	mmh 2008	mmh 2011
Berlin		7.95 %	6.45 %	8.95 %	2.18 %	1.29 %	0.83 %	1.53 %	0.08 %	0.06 %	0.06 %
Chemnitz	1	7.86 %	5.38 %	4.60 %	2.75 %	1.00 %	1.42 %	2.02 %	0.28 %	0.10 %	0.10 %
Dresden	1	8.38 %	6.38 %	8.98 %	2.56 %	0.97 %	2.06 %	3.40 %	0.21 %	0.17 %	0.19 %
Erfurt	1	9.76 %	5.98 %	0.76 %	4.29 %	2.59 %	1.51 %	2.61 %	0.38 %	0.22 %	0.13 %
Halle	1	9.43 %	5.19 %	4.58 %	6.73 %	2.33 %	0.51 %	1.71 %	0.33 %	0.13 %	0.09 %
Jena	1	3.61 %	3.43 %	9.77 %	4.02 %	2.51 %	1.35 %	1.45 %	0.38 %	0.44 %	0.33 %
Leipzig	1	5.18 %	7.92 %	6.66 %	2.52 %	1.75 %	1.28 %	2.78 %	0.25 %	0.23 %	0.16 %
Magdeburg	1	4.81 %	4.77 %	2.20 %	4.81 %	0.67 %	1.40 %	2.67 %	0.20 %	0.14 %	0.08 %
Potsdam	1	5.19 %	2.44 %	9.90 %	7.20 %	1.88 %	1.66 %	3.48 %	0.72 %	0.74 %	0.32 %
Rostock	1	3.35 %	6.68 %	2.20 %	4.86 %	2.51 %	0.80 %	1.99 %	0.57 %	0.36 %	0.07 %
Bergisch Gladbach	1	0.10 %	0.00 %	5.44 %	0.98 %	0.20 %	1.60 %	1.25 %	0.59 %	0.27 %	0.10 %
Bottrop	2	0.19 %	0.77 %	6.27 %	1.24 %	0.46 %	0.75 %	1.76 %	0.44 %	0.28 %	0.25 %
Hamm	2	0.16 %	0.50 %	6.43 %	1.20 %	0.20 %	0.97 %	1.01 %	0.21 %	0.11 %	0.00 %
Leverkusen	2	0.66 %	0.58 %	3.48 %	1.55 %	0.52 %	1.76 %	1.17 %	0.67 %	0.21 %	0.16 %
Moers	2	0.22 %	0.12 %	7.69 %	1.86 %	0.50 %	0.75 %	1.43 %	0.29 %	0.07 %	0.07 %
Heilbronn	2	0.37 %	0.60 %	9.16 %	1.78 %	0.73 %	1.68 %	0.84 %	0.65 %	0.41 %	0.03 %
Ingolstadt	3	0.40 %	0.35 %	6.81 %	0.82 %	0.70 %	2.07 %	1.60 %	0.72 %	0.47 %	0.10 %
Neuss	3	0.49 %	0.43 %	9.92 %	1.45 %	0.33 %	1.55 %	2.67 %	0.45 %	0.30 %	0.15 %
Oldenburg	3	0.39 %	0.04 %	5.85 %	1.51 %	0.44 %	1.25 %	0.62 %	0.02 %	0.10 %	0.00 %
Paderborn	3	0.20 %	0.22 %	5.69 %	1.73 %	0.50 %	1.93 %	1.46 %	0.61 %	0.25 %	0.10 %
Reutlingen	3	0.39 %	0.18 %	5.33 %	2.20 %	0.64 %	1.91 %	1.44 %	0.07 %	0.55 %	0.15 %
Wolfsburg	3	0.21 %	2.15 %	2.52 %	0.65 %	0.61 %	0.94 %	0.63 %	0.03 %	0.04 %	0.00 %
Bielefeld	3	1.74 %	1.18 %	7.66 %	1.74 %	0.27 %	1.05 %	0.96 %	0.28 %	0.41 %	0.18 %
Bonn	4	1.38 %	0.68 %	8.10 %	2.42 %	0.57 %	1.25 %	1.27 %	0.19 %	0.21 %	0.10 %
Erlangen	4	0.93 %	0.22 %	1.47 %	1.89 %	0.89 %	1.68 %	0.83 %	0.64 %	0.88 %	0.17 %
Fürth	4	7.68 %	3.03 %	8.81 %	2.31 %	0.67 %	1.89 %	0.61 %	0.76 %	0.44 %	0.27 %
Mainz	4	1.67 %	1.62 %	1.63 %	1.12 %	0.56 %	1.09 %	0.95 %	0.50 %	0.43 %	0.16 %
Münster	4	0.66 %	1.69 %	1.61 %	1.85 %	0.36 %	1.23 %	1.24 %	0.50 %	0.29 %	0.22 %
Ulm	4	1.20 %	2.22 %	9.24 %	1.83 %	1.02 %	1.77 %	0.89 %	0.59 %	0.35 %	0.31 %
Würzburg	4	1.18 %	1.88 %	6.68 %	1.98 %	0.55 %	1.04 %	0.69 %	0.20 %	0.19 %	0.11 %
Augsburg	4	4.43 %	2.66 %	2.49 %	3.01 %	1.39 %	1.80 %	1.23 %	0.32 %	0.22 %	0.21 %
Düsseldorf	5	3.85 %	4.16 %	9.18 %	2.33 %	0.41 %	1.41 %	1.18 %	0.52 %	0.36 %	0.20 %
Frankfurt am Main	5	6.82 %	3.53 %	5.62 %	1.25 %	0.50 %	0.93 %	0.94 %	0.59 %	0.56 %	0.26 %
Freiburg im Breisgau	5	1.65 %	2.29 %	0.73 %	1.83 %	0.50 %	1.28 %	1.75 %	0.86 %	0.98 %	0.22 %
Hamburg	5	4.35 %	3.84 %	5.85 %	1.89 %	0.44 %	0.96 %	1.46 %	0.40 %	0.34 %	0.20 %
Hannover	5	6.66 %	6.69 %	8.64 %	1.88 %	0.44 %	1.21 %	1.38 %	0.22 %	0.22 %	0.11 %
Heidelberg	5	4.45 %	1.93 %	7.22 %	1.40 %	0.25 %	1.12 %	1.29 %	0.39 %	0.48 %	0.17 %
Karlsruhe	5	5.28 %	3.73 %	1.68 %	1.80 %	0.42 %	1.04 %	0.89 %	0.28 %	0.31 %	0.18 %
Kiel	5	9.73 %	5.00 %	3.71 %	1.37 %	0.22 %	0.84 %	0.99 %	0.23 %	0.10 %	0.07 %
Köln	5	2.97 %	3.89 %	5.33 %	1.58 %	0.35 %	1.11 %	1.54 %	0.65 %	0.84 %	0.42 %
Mannheim	5	4.24 %	3.45 %	4.47 %	1.72 %	0.59 %	1.67 %	1.19 %	0.29 %	0.26 %	0.07 %
München	5	3.43 %	3.72 %	9.54 %	2.12 %	1.00 %	1.30 %	1.18 %	0.67 %	0.69 %	0.40 %
Nürnberg	5	5.90 %	3.15 %	4.95 %	1.64 %	0.55 %	1.11 %	0.55 %	0.33 %	0.33 %	0.16 %
Offenbach am Main	5	6.18 %	2.95 %	0.83 %	1.71 %	0.58 %	0.87 %	0.92 %	0.29 %	0.09 %	0.11 %
Regensburg	5	3.35 %	2.34 %	1.01 %	2.05 %	1.16 %	2.35 %	1.60 %	0.78 %	1.01 %	0.31 %
Stuttgart	5	5.37 %	3.53 %	0.29 %	1.80 %	0.71 %	1.40 %	1.30 %	0.46 %	0.48 %	0.35 %
Aachen	5	3.82 %	2.37 %	3.70 %	1.84 %	0.33 %	1.10 %	0.69 %	0.35 %	0.15 %	0.11 %
Braunschweig	6	7.60 %	3.64 %	3.69 %	1.53 %	0.22 %	0.60 %	0.56 %	0.21 %	0.34 %	0.07 %
Bremerhaven	6	4.29 %	4.43 %	8.61 %	1.02 %	0.10 %	0.65 %	0.29 %	0.24 %	0.06 %	0.00 %
Darmstadt	6	2.08 %	1.94 %	2.80 %	1.87 %	0.77 %	1.07 %	1.09 %	0.38 %	0.43 %	0.18 %
Dortmund	6	3.59 %	3.22 %	3.48 %	1.59 %	0.31 %	0.79 %	1.09 %	0.29 %	0.13 %	0.07 %
Göttingen	6	3.64 %	2.02 %	1.51 %	1.64 %	0.63 %	0.95 %	0.63 %	0.28 %	0.34 %	0.03 %
Hagen	6	3.95 %	2.94 %	4.87 %	1.45 %	0.43 %	0.69 %	1.09 %	0.31 %	0.13 %	0.02 %
Kassel	6	3.57 %	3.48 %	3.32 %	0.85 %	0.07 %	1.36 %	1.06 %	0.28 %	0.19 %	0.06 %
Lübeck	6	2.25 %	2.31 %	1.06 %	0.99 %	0.58 %	0.89 %	1.03 %	0.78 %	0.45 %	0.19 %
Ludwigshafen am Rhein	6	1.61 %	2.46 %	2.20 %	1.47 %	0.39 %	1.79 %	0.62 %	0.29 %	0.08 %	0.15 %
Trier	6	1.64 %	1.23 %	6.80 %	2.28 %	0.87 %	1.00 %	0.93 %	0.32 %	0.42 %	0.23 %
Wiesbaden	6	6.67 %	1.89 %	2.15 %	1.13 %	0.65 %	1.04 %	1.59 %	0.54 %	0.45 %	0.14 %
Wuppertal	6	5.47 %	2.05 %	5.81 %	1.24 %	0.36 %	0.86 %	0.88 %	0.29 %	0.16 %	0.03 %
Krefeld	6	1.90 %	1.38 %	0.45 %	1.80 %	0.30 %	0.72 %	1.41 %	0.24 %	0.09 %	0.09 %
Mönchengladbach	7	0.53 %	0.46 %	8.48 %	2.26 %	0.45 %	1.44 %	0.99 %	0.27 %	0.16 %	0.12 %
Mülheim an der Ruhr	7	0.58 %	1.41 %	1.75 %	1.81 %	0.32 %	0.93 %	0.94 %	0.50 %	0.14 %	0.05 %
Oberhausen	7	1.14 %	1.00 %	0.12 %	1.91 %	0.29 %	0.62 %	1.36 %	0.33 %	0.18 %	0.22 %
Osnabrück	7	1.43 %	1.68 %	1.05 %	1.25 %	0.21 %	1.22 %	1.03 %	0.12 %	0.08 %	0.00 %
Pforzheim	7	0.94 %	1.82 %	2.39 %	1.96 %	0.70 %	2.60 %	0.85 %	0.20 %	0.19 %	0.10 %
Recklinghausen	7	1.10 %	0.97 %	8.81 %	3.05 %	0.33 %	0.97 %	1.03 %	0.30 %	0.03 %	0.00 %
Remscheid	7	1.06 %	1.14 %	4.33 %	1.14 %	0.20 %	0.88 %	1.24 %	0.26 %	0.03 %	0.07 %
Solingen	7	0.88 %	0.54 %	7.84 %	1.23 %	0.33 %	1.02 %	1.46 %	0.85 %	0.21 %	0.00 %
Bochum	7	2.17 %	2.47 %	4.33 %	1.99 %	0.42 %	0.90 %	0.88 %	0.22 %	0.14 %	0.06 %
Bremen	8	0.68 %	0.90 %	1.78 %	1.09 %	0.28 %	0.87 %	0.91 %	0.22 %	0.10 %	0.10 %
Duisburg	8	1.58 %	2.25 %	5.97 %	1.75 %	0.33 %	0.81 %	0.91 %	0.44 %	0.19 %	0.03 %
Essen	8	1.90 %	2.95 %	7.60 %	1.69 %	0.27 %	0.69 %	0.70 %	0.27 %	0.14 %	0.05 %
Gelsenkirchen	8	3.03 %	2.27 %	7.70 %	1.78 %	0.29 %	1.05 %	1.04 %	0.18 %	0.08 %	0.03 %
Herne	8	4.07 %	3.64 %	2.79 %	1.69 %	0.11 %	1.45 %	1.35 %	0.34 %	0.00 %	0.00 %
Koblenz	8	1.53 %	1.35 %	0.31 %	1.53 %	0.22 %	1.40 %	0.97 %	0.13 %	0.43 %	0.13 %
Saarbrücken	8	1.74 %	1.79 %	8.58 %	1.33 %	0.11 %	0.56 %	0.47 %	0.15 %	0.08 %	0.03 %

Table 28: share of floor area of row houses by city

city	cluster id	rh 1919	rh 1948	rh 1978	rh 1986	rh 1990	rh 1995	rh 2000	rh 2004	rh 2008	rh 2011
Berlin		0.18 %	0.76 %	0.95 %	0.29 %	0.12 %	0.08 %	0.27 %	0.18 %	0.15 %	0.09 %
Chemnitz	1	0.13 %	1.14 %	0.04 %	0.02 %	0.05 %	0.10 %	0.63 %	0.13 %	0.05 %	0.05 %
Dresden	1	0.33 %	0.93 %	0.07 %	0.02 %	0.04 %	0.30 %	0.73 %	0.25 %	0.10 %	0.05 %
Erfurt	1	1.17 %	1.72 %	0.32 %	0.11 %	0.06 %	0.60 %	1.51 %	0.43 %	0.15 %	0.10 %
Halle	1	0.76 %	2.29 %	0.40 %	0.15 %	0.04 %	0.17 %	0.81 %	0.39 %	0.09 %	0.02 %
Jena	1	1.15 %	0.99 %	0.62 %	0.05 %	0.00 %	0.48 %	0.42 %	0.48 %	0.26 %	0.02 %
Leipzig	1	0.28 %	0.85 %	0.17 %	0.04 %	0.01 %	0.15 %	0.94 %	0.28 %	0.12 %	0.07 %
Magdeburg	1	0.49 %	2.19 %	0.76 %	0.22 %	0.07 %	0.14 %	0.69 %	0.36 %	0.06 %	0.07 %
Potsdam	1	0.67 %	0.65 %	0.18 %	0.06 %	0.02 %	0.17 %	0.88 %	0.45 %	0.42 %	0.43 %
Rostock	1	0.42 %	0.66 %	0.32 %	0.16 %	0.15 %	0.23 %	1.89 %	0.75 %	0.36 %	0.10 %
Bergisch Gladbach	1	0.54 %	0.72 %	6.77 %	2.44 %	0.77 %	0.75 %	0.53 %	0.50 %	0.34 %	0.04 %
Bottrop	2	1.74 %	1.36 %	4.40 %	1.87 %	0.99 %	0.48 %	0.89 %	0.73 %	0.35 %	0.24 %
Hamm	2	1.14 %	1.30 %	4.60 %	1.41 %	0.25 %	0.46 %	0.60 %	0.36 %	0.34 %	0.12 %
Leverkusen	2	1.99 %	0.99 %	4.80 %	1.47 %	0.91 %	0.61 %	0.67 %	0.89 %	0.58 %	0.26 %
Moers	2	2.42 %	0.71 %	7.81 %	2.51 %	1.47 %	1.01 %	1.34 %	0.43 %	0.29 %	0.08 %
Heilbronn	2	0.23 %	0.43 %	4.09 %	1.41 %	0.45 %	0.31 %	0.40 %	0.48 %	0.35 %	0.02 %
Ingolstadt	3	0.32 %	0.26 %	3.14 %	2.07 %	0.82 %	0.86 %	0.74 %	0.36 %	0.54 %	0.33 %
Neuss	3	1.70 %	1.67 %	0.20 %	2.33 %	1.20 %	0.98 %	1.65 %	1.11 %	0.50 %	0.24 %
Oldenburg	3	0.12 %	0.26 %	3.88 %	1.19 %	0.41 %	0.45 %	0.94 %	0.19 %	0.14 %	0.06 %
Paderborn	3	0.11 %	0.22 %	3.58 %	1.70 %	1.03 %	0.91 %	1.12 %	0.68 %	0.78 %	0.19 %
Reutlingen	3	0.49 %	0.67 %	2.20 %	1.02 %	0.58 %	0.40 %	0.48 %	0.35 %	0.57 %	0.13 %
Wolfsburg	3	0.22 %	0.58 %	5.33 %	0.82 %	0.51 %	0.41 %	1.41 %	0.48 %	0.45 %	0.10 %
Bielefeld	3	0.18 %	0.29 %	5.32 %	1.58 %	0.41 %	0.26 %	0.71 %	0.41 %	0.23 %	0.07 %
Bonn	4	2.51 %	1.32 %	5.84 %	2.32 %	0.76 %	0.71 %	0.55 %	0.40 %	0.52 %	0.34 %
Erlangen	4	0.72 %	0.54 %	5.65 %	1.60 %	0.37 %	0.66 %	0.81 %	0.78 %	0.66 %	0.25 %
Fürth	4	0.40 %	0.46 %	3.68 %	2.75 %	0.78 %	0.35 %	0.59 %	0.96 %	0.28 %	0.28 %
Mainz	4	0.69 %	0.59 %	4.64 %	1.80 %	0.94 %	0.49 %	1.22 %	0.44 %	0.62 %	0.20 %
Münster	4	0.15 %	0.71 %	5.58 %	2.06 %	0.71 %	0.60 %	1.01 %	0.72 %	0.75 %	0.29 %
Ulm	4	0.72 %	0.57 %	5.46 %	2.08 %	1.11 %	1.14 %	1.52 %	0.54 %	0.29 %	0.07 %
Würzburg	4	0.13 %	0.50 %	3.49 %	1.53 %	0.80 %	0.56 %	0.44 %	0.47 %	0.23 %	0.04 %
Augsburg	4	0.50 %	0.71 %	5.71 %	1.56 %	0.56 %	0.44 %	0.38 %	0.30 %	0.29 %	0.14 %
Düsseldorf	5	0.75 %	1.36 %	2.92 %	1.01 %	0.57 %	0.31 %	0.31 %	0.53 %	0.32 %	0.19 %
Frankfurt am Main	5	0.53 %	2.15 %	2.88 %	0.50 %	0.35 %	0.15 %	0.54 %	0.59 %	0.58 %	0.07 %
Freiburg im Breisgau	5	0.67 %	0.82 %	2.61 %	1.06 %	0.46 %	0.31 %	0.65 %	0.62 %	0.47 %	0.14 %
Hamburg	5	0.32 %	0.56 %	5.33 %	0.87 %	0.39 %	0.34 %	0.45 %	0.43 %	0.40 %	0.14 %
Hannover	5	0.19 %	0.78 %	4.26 %	1.10 %	0.75 %	0.54 %	0.80 %	0.61 %	0.42 %	0.11 %
Heidelberg	5	1.28 %	2.04 %	2.65 %	1.47 %	0.51 %	0.37 %	0.27 %	0.48 %	0.36 %	0.18 %
Karlsruhe	5	0.79 %	1.09 %	3.32 %	1.46 %	0.69 %	0.72 %	0.61 %	0.40 %	0.50 %	0.13 %
Kiel	5	0.16 %	1.95 %	4.09 %	1.63 %	0.88 %	0.59 %	0.39 %	0.41 %	0.27 %	0.19 %
Köln	5	0.76 %	1.85 %	5.40 %	1.41 %	0.51 %	0.47 %	0.59 %	0.50 %	0.45 %	0.33 %
Mannheim	5	0.94 %	1.81 %	3.62 %	1.80 %	0.50 %	0.51 %	0.56 %	0.44 %	0.25 %	0.05 %
München	5	0.23 %	0.43 %	2.80 %	1.04 %	0.29 %	0.14 %	0.32 %	0.30 %	0.33 %	0.12 %
Nürnberg	5	0.29 %	1.70 %	7.04 %	1.46 %	0.44 %	0.35 %	0.39 %	0.50 %	0.49 %	0.22 %
Offenbach am Main	5	0.41 %	0.71 %	2.41 %	0.93 %	0.15 %	0.20 %	0.32 %	0.52 %	0.24 %	0.07 %
Regensburg	5	0.39 %	0.36 %	3.71 %	0.98 %	0.41 %	0.62 %	0.66 %	0.71 %	0.77 %	0.34 %
Stuttgart	5	0.25 %	0.81 %	2.13 %	0.68 %	0.36 %	0.19 %	0.42 %	0.36 %	0.36 %	0.09 %
Aachen	5	1.45 %	1.62 %	5.66 %	1.50 %	0.72 %	0.46 %	0.56 %	0.47 %	0.24 %	0.16 %
Braunschweig	6	0.16 %	0.83 %	5.88 %	0.89 %	0.42 %	0.27 %	0.49 %	0.37 %	0.32 %	0.05 %
Bremerhaven	6	0.35 %	1.39 %	5.08 %	0.78 %	0.08 %	0.12 %	0.46 %	0.15 %	0.18 %	0.01 %
Darmstadt	6	0.32 %	0.66 %	4.45 %	1.43 %	0.52 %	0.36 %	0.69 %	0.94 %	0.87 %	0.05 %
Dortmund	6	0.65 %	0.92 %	5.27 %	1.28 %	0.41 %	0.28 %	0.83 %	0.67 %	0.27 %	0.12 %
Göttingen	6	0.60 %	0.82 %	5.30 %	1.82 %	0.74 %	0.57 %	1.15 %	0.46 %	0.26 %	0.07 %
Hagen	6	0.35 %	0.53 %	3.70 %	1.25 %	0.27 %	0.10 %	0.53 %	0.39 %	0.19 %	0.06 %
Kassel	6	0.31 %	1.68 %	3.48 %	1.01 %	0.34 %	0.38 %	0.60 %	0.32 %	0.08 %	0.01 %
Lübeck	6	2.70 %	1.44 %	6.24 %	0.97 %	0.59 %	0.49 %	0.87 %	0.53 %	0.71 %	0.28 %
Ludwigshafen am Rhein	6	0.99 %	2.76 %	4.48 %	1.57 %	1.30 %	0.95 %	0.70 %	0.51 %	0.49 %	0.12 %
Trier	6	3.62 %	3.05 %	5.89 %	1.31 %	0.74 %	0.72 %	0.77 %	0.54 %	0.40 %	0.16 %
Wiesbaden	6	0.80 %	0.65 %	3.83 %	1.53 %	0.65 %	0.32 %	0.53 %	0.52 %	0.53 %	0.20 %
Wuppertal	6	0.77 %	1.08 %	3.97 %	1.62 %	0.37 %	0.31 %	0.33 %	0.57 %	0.21 %	0.11 %
Krefeld	6	2.15 %	2.27 %	6.98 %	2.00 %	0.78 %	0.55 %	0.83 %	0.95 %	0.29 %	0.11 %
Mönchengladbach	7	3.75 %	2.73 %	7.83 %	2.36 %	0.88 %	0.73 %	0.91 %	0.63 %	0.34 %	0.17 %
Mülheim an der Ruhr	7	1.18 %	1.47 %	4.97 %	1.07 %	0.54 %	0.48 %	0.61 %	0.46 %	0.72 %	0.18 %
Oberhausen	7	1.73 %	1.15 %	4.14 %	1.58 %	0.81 %	0.70 %	1.23 %	0.69 %	0.49 %	0.07 %
Osnabrück	7	0.33 %	0.58 %	6.44 %	1.55 %	0.36 %	0.44 %	0.64 %	0.57 %	0.33 %	0.03 %
Pforzheim	7	0.72 %	0.87 %	3.22 %	0.91 %	0.60 %	0.38 %	0.58 %	0.35 %	0.34 %	0.01 %
Recklinghausen	7	1.04 %	1.04 %	5.62 %	1.76 %	0.82 %	0.86 %	0.87 %	0.42 %	0.39 %	0.16 %
Remscheid	7	0.55 %	0.60 %	4.34 %	1.40 %	0.61 %	0.71 %	0.44 %	0.38 %	0.21 %	0.04 %
Solingen	7	1.23 %	0.64 %	3.11 %	1.19 %	0.51 %	0.49 %	0.49 %	0.75 %	0.74 %	0.17 %
Bochum	7	0.60 %	1.06 %	4.68 %	1.41 %	0.62 %	0.43 %	0.72 %	0.42 %	0.42 %	0.14 %
Bremen	8	4.03 %	4.62 %	0.23 %	1.60 %	0.54 %	0.72 %	0.93 %	0.64 %	0.51 %	0.16 %
Duisburg	8	1.80 %	3.00 %	3.99 %	1.13 %	0.48 %	0.66 %	0.64 %	0.72 %	0.32 %	0.08 %
Essen	8	1.31 %	1.44 %	3.81 %	1.29 %	0.62 %	0.31 %	0.43 %	0.37 %	0.38 %	0.13 %
Gelsenkirchen	8	1.43 %	1.70 %	3.47 %	1.04 %	0.64 %	0.39 %	0.93 %	0.34 %	0.35 %	0.15 %
Herne	8	1.03 %	1.48 %	3.38 %	1.24 %	0.62 %	0.51 %	0.89 %	0.43 %	0.28 %	0.12 %
Koblenz	8	1.65 %	1.10 %	5.10 %	1.37 %	0.40 %	0.45 %	0.50 %	0.41 %	0.32 %	0.16 %
Saarbrücken	8	2.50 %	2.57 %	5.16 %	0.86 %	0.18 %	0.18 %	0.42 %	0.18 %	0.18 %	0.01 %

A Appendix

A.1 Source Code

The following model parts integrate census city data with growth factors. It was written in python[83] on jupyter notebook[84]. This allows to combine notes with code. The model consists of a main part to calculate population and floor area changes and three modules "weightnew", "grow" and "shri" to determine the population distribution in buildings.

A.1.1 calculate population and floor area changes

```
This program part ... implements the growth and m2/cap changes

    (A) calculates the population change
    (B) Define new buildings for growth and lower use intensity
    (C) Redistribute population moving from existing into new buildings
    (D) Determine total population in new building segments
    (E) Calculate population shrinkage in bseg due to shrinking

(1) Import packages
```

```
path='/home/benutzer/Dokumente/poliwarm/Dissertation/trunk/_Analysen/ipython'
import numpy as np # matrix paket
import pandas as pd # working with Excel files
pd.set_option('display.multi_sparse', False) # printoption: repeating names of aggregated
    fields
pd.options.display.float_format = '{:,.2f}'.format
import D_Growth_Modules.weightnew as weight # own module
import D_Growth_Modules.grow as grow  # own module
import D_Growth_Modules.shri as shri  # own module
import imp
```

```
(2) Read sources
```

```
bert      = pd.read_excel(path + '/C_Growth/INPUT/bertelsmann_daten.xlsx'
                        ,'values', header=0, index_col=0, na_values=['NA'])
zensus_cibtow = pd.read_excel(path + '/C_Growth/INTERFILES/zensus_cibtow.xlsx',
                        'Sheet1', header=0, index_col=(0,1,2,3), na_values=['NA'])
iterables = [zensus_cibtow.index.levels[1],zensus_cibtow.index.levels[2]]
btypes = pd.MultiIndex.from_product(iterables, names=['bcat','bage']).values
```

```
(A) Calculate total population change
```

```
bert['population change %'] = bert['population change 2011-2030'] / 100
def separate(a):
   g = max(0,a / 100)
   s = min(0,a / 100)
#   if a > 0: g == a
```

[83] Python 2.7.13 |Anaconda 4.3.1 (32-bit)| (default, Dec 20 2016, 23:08:16) [GCC 4.4.7 20120313 (Red Hat 4.4.7-1)]
[84] notebook server 4.3.1

```
#    else: s = a
    return g,s
arr_a = np.array([separate(c) for c in bert['population change 2011-2030']])
bert['population growth %'],bert['population shrink %'] = arr_a[:,0],arr_a[:,1]


bert['population change'] = bert['population 2011'] * bert['population change %']
bert['population growth'] = bert['population 2011'] * bert['population growth %']
bert['population shrink'] = bert['population 2011'] * bert['population shrink %']
bert['population 2030'] = bert['population 2011'] + bert['population change']

dict_popgrow_ci = dict( bert['population growth'])
dict_popshri_ci = dict( bert['population shrink'])
dict_popchge_ci = dict( bert['population change'])
```

(B) Define new building segments

Calculate weight of new buildings based on population share in 2011-buildings

```
zensus_cibtow['year'] = 2010
zensus_cibtow['scen'] = 'BAU'

weight = imp.reload(weight)
wensus_cibtow = weight.func(zensus_cibtow) # calculates weight for new building segments and
                                           # appends them to the building stock dataframe
if sum(wensus_cibtow['weight']).round(0) != 76:
    print('weight is off')
```

(C) Redistribute population moving from existing into new buildings

```
# determine population IN EXISTING BUILDINGS
dict_m2p2030 = dict(bert['m2/cap 2030'])
dict_m2p2011 = dict(bert['m2/cap 2011'])

## POPULATION SCENARIOS
## GROW: ogro = scenario includes only growth
## GRIN: m2gr = scenario includes use intensity (m2p) change and growth
wensus_cibtow['pop in exib m2gr'] = wensus_cibtow['floor area'] /
    (wensus_cibtow.index.get_level_values(0)
                                                          .map(lambda x:dict_m2p2030[x]))
wensus_cibtow['pop in exib Ogro'] = wensus_cibtow['floor area'] /
    (wensus_cibtow.index.get_level_values(0)
                                                          .map(lambda x:dict_m2p2011[x]))
# population redistribution = population before use intensity change - population in existing
dict_pop_in_exib    = dict(wensus_cibtow.groupby(level=['city'])['pop in exib m2gr'].sum())
dict_pop_in_exib_Ogro = dict(wensus_cibtow.groupby(level=['city'])['pop in exib Ogro'].sum())

bert['pop 2030 in existing buildings m2gr'] = bert.index.map(lambda x: dict_pop_in_exib[x])
bert['pop 2030 in existing buildings Ogro'] = bert.index.map(lambda x:
    dict_pop_in_exib_Ogro[x])

bert['pop redistribution'] = bert['population 2011'] - bert['pop 2030 in existing buildings
    m2gr']
```

```
dict_redist = dict(bert['pop redistribution'])

# determine NEWBuilding POPulation and POPulation REDUCTION in EXIstingBuildings
bert['pop in new buildings m2gr']    =(bert['population change'] + bert['pop
    redistribution']).clip(lower=0)
bert['population reduction m2gr']    =(bert['population change'] + bert['pop
    redistribution']).clip(upper=0)
dict_popredu_ci      = dict(bert['population reduction m2gr'])
dict_popnewb_ci      = dict(bert['pop in new buildings m2gr'])

bert['pop in new buildings Ogro'] = bert['population change'].clip(lower=0)
bert['population reduction Ogro'] = bert['population change'].clip(upper=0)
dict_popredu_ci_Ogro = dict(bert['population reduction Ogro'])
dict_popnewb_ci_Ogro = dict(bert['pop in new buildings Ogro'])

bert['pop in new buildings Om2p'] = bert['pop redistribution'].clip(lower=0)
bert['population reduction Om2p'] = bert['pop redistribution'].clip(upper=0)
dict_popredu_ci_Om2p = dict(bert['population reduction Om2p'])
dict_popnewb_ci_Om2p = dict(bert['pop in new buildings Om2p'])
```

(D) Determine total population in new building segments

```
#### GRIN: Growth and use intensity Change #### #
# ALLOCATE POPulationGROWTH to building segment based on their weight previously determined
wensus_cibtow['pop newb m2gr'] = (wensus_cibtow['weight']
                         * wensus_cibtow.index.get_level_values(0)
                         .map(lambda x: dict_popnewb_ci[x])
                        )
wensus_cibtow['popGrowth'] = (wensus_cibtow['weight']
                         * wensus_cibtow.index.get_level_values(0)
                         .map(lambda x: dict_popgrow_ci[x])
                        )
wensus_cibtow['popRedist m2gr'] = (wensus_cibtow['weight']
                         * wensus_cibtow.index.get_level_values(0)
                         .map(lambda x: dict_redist[x])
                        )

#### GROW: Growth only #### #
# ALLOCATE POPulationGROWTH to building segment based on their weight previously determined
wensus_cibtow['pop newb Ogro'] = (wensus_cibtow['weight']
                              * wensus_cibtow.index.get_level_values(0)
                              .map(lambda x: dict_popnewb_ci_Ogro[x])
                             )
wensus_cibtow['popRedist Ogro'] = 0
```

(E) Calculate population shrinkage in bseg due to shrinking

```
shri = imp.reload(shri) # reload module
shri.func(wensus_cibtow, dict_popredu_ci, btypes, np, ' m2gr')
shri.func(wensus_cibtow, dict_popredu_ci_Ogro, btypes, np, ' Ogro')
shri.func(wensus_cibtow, dict_popredu_ci_Om2p, btypes, np, ' Om2p')

wensus_cibtow.replace({np.nan: 0},inplace=True)
```

```
#df_ebs_btow[df_ebs_btow['immobile population shrinkage']!=0][:4] # only cities where also
    the immobile pop shrinks

### ADDING POPulation CHANGES
wensus_cibtow['pop 2030 m2gr'] = (wensus_cibtow['pop in exib m2gr']
                              + wensus_cibtow['pop newb m2gr']
                              + wensus_cibtow['popShrink m2gr'])
wensus_cibtow['pop 2030 Ogro'] = (wensus_cibtow['pop in exib Ogro']
                              + wensus_cibtow['pop newb Ogro']
                              + wensus_cibtow['popShrink Ogro'])

wensus_cibtow['fla 2030 m2gr'] = (wensus_cibtow['pop 2030 m2gr'] *
                              (wensus_cibtow.index.get_level_values(0)
                               .map(lambda x:dict_m2p2030[x]))
                             )
wensus_cibtow['fla 2030 Ogro'] = (wensus_cibtow['pop 2030 Ogro'] *
                              (wensus_cibtow.index.get_level_values(0)
                               .map(lambda x:dict_m2p2011[x]))
                             )
wensus_cibtow.replace({np.nan: 0},inplace=True)

### Checks
share_fla_m2gr = (wensus_cibtow.query('year == 2030')['fla 2030 m2gr'].sum()
           / wensus_cibtow.query('year == 2010')['fla 2030 m2gr'].sum())
share_pop_m2gr = (wensus_cibtow.query('year == 2030')['pop 2030 m2gr'].sum()
           / wensus_cibtow.query('year == 2010')['pop 2030 m2gr'].sum())
# CHECK
if abs((share_fla_m2gr / share_pop_m2gr)-1) > 0.05:
    print('check floor area in 2030 for new building segments')
    print(share_fla)
    print(share_pop)
share_fla_Ogro = (wensus_cibtow.query('year == 2030')['fla 2030 Ogro'].sum()
           / wensus_cibtow.query('year == 2010')['fla 2030 Ogro'].sum())
share_pop_Ogro = (wensus_cibtow.query('year == 2030')['pop 2030 Ogro'].sum()
           / wensus_cibtow.query('year == 2010')['pop 2030 Ogro'].sum())
# CHECK
if abs((share_fla_m2gr / share_pop_m2gr)-1) > 0.05:
    print('check floor area in 2030 for new building segments')
    print(share_fla_Ogro)
    print(share_pop_Ogro)
share_fla_Om2p = (wensus_cibtow.query('year == 2030')['fla 2030 Om2p'].sum()
           / wensus_cibtow.query('year == 2010')['fla 2030 Om2p'].sum())
share_pop_Om2p = (wensus_cibtow.query('year == 2030')['pop 2030 Om2p'].sum()
           / wensus_cibtow.query('year == 2010')['pop 2030 Om2p'].sum())
# CHECK
if abs((share_fla_m2gr / share_pop_m2gr)-1) > 0.05:
    print('check floor area in 2030 for new building segments')
    print(share_fla_Om2p)
    print(share_pop_Om2p)
```

A.1.2 weightnew

```
# coding: utf-8
```

```python
# (B) Calculate weight of new buildings based on pop share 2011-buildings

#* in new bs
#* input 1: dataframe with current population and building stock
#* processing 1: determine weight of building segments based on latest building segment
#* processing 2: assign population growth according to weight
#* processing 3: establish and format new building segments
#* processing 4: new building segments have geometry and energy demand of last years building
    segments
#* output: dataframe to be appended to current building stock


def func(df_cibtow):
    df_cibtow['weight'] = 0
    df_growth_new_bs = (df_cibtow.query('bage == 2011')
                         .reset_index()
                        )
    # DATA PREPARATION
    ## set pop = 00 so the new segments have no pop in 2011
    ## Therefore, rename column 'pop2011' instead of 'pop',
    ## because this will be appended to other dataframe
    df_growth_new_bs['pop2011']=df_growth_new_bs['pop']
    df_growth_new_bs['pop'] = 0
    df_growth_new_bs['scen'] = 0
    df_growth_new_bs['floor area'] = 0
    df_growth_new_bs['GEB'] = 0
    df_growth_new_bs['year'] = 2030
    ## set bage to 2030 instead of 2011
    df_growth_new_bs['bage']=2030
    ## after this, we can set the index
    ## if we'd do it before, we could not change the bage
    ## because indexes cannot be changed
    df_growth_new_bs.set_index(['city','bcat','bage','owner'], inplace=True)


    # WEIGHT CALCULATION
    # Calculate the weight: population share by 2011 building segment compared to all bs of
        2011
    ## sum of population of all building segments of 2011 (for one city)
    dict_pop2011 = dict(df_cibtow.query('bage == 2011').groupby(level=('city'))['pop'].sum())
    ## calculation of population share per building segment
    df_growth_new_bs['weight'] = (df_growth_new_bs['pop2011']
         / df_growth_new_bs.index.get_level_values('city').map(lambda x:dict_pop2011[x])
         )
    # FILL
    ## fill btype and btype_owner because they are needed for df_ebs_grow
    for e,n in enumerate(df_growth_new_bs.index):
        df_growth_new_bs.loc[n,'btype'] = n[1] + '_' + str(n[2])
        df_growth_new_bs.loc[n,'btype_owner'] = n[1] + '_' + str(n[2]) + '_' + n[3]

    df_growth_newbs = df_growth_new_bs[df_cibtow.columns]
    df_cibtow = df_cibtow.append(df_growth_newbs)
    return df_cibtow
```

A.1.3 grow

```
# coding: utf-8
def dictio(dict,city):
    return dict[city]

def dafra(df):
    df_growth_new_bs = ( df.query('bage == 2011')
                        .groupby(level=(0,1,2,3))['pop']
                        .sum()
                        .to_frame(name = 'pop')
                        .reset_index())
    return df_growth_new_bs

def func(df_cibtow, dict_popgrow_ci):
    df_growth_new_bs = (df_cibtow.query('bage == 2011')
                    .groupby(level=(0,1,2,3))['pop']
                    .sum()
                    .to_frame(name = 'pop')
                    .reset_index()                  )

    # DATA PREPARATION
    ## set pop = 00 so the new segments have no pop in 2011
    ## Therefore, rename column 'pop2011' instead of 'pop',
    ## because this will be appended to other dataframe
    df_growth_new_bs['pop2011']=df_growth_new_bs['pop']
    df_growth_new_bs['pop'] = 0
    ## set bage to 2030 instead of 2011
    df_growth_new_bs['bage']=2030
    ## after this, we can set the index
    ## if we'd do it before, we could not change the bage
    ## because indexes cannot be changed
    df_growth_new_bs = df_growth_new_bs.set_index(['city','bsize','bage','owner'],
        inplace=False)

    # WEIGHT CALCULATION
    # Calculate the weight: population share by 2011 building segment compared to all bs of
        2011
    ## sum of population of all building segments of 2011 (for one city)
    dict_pop2011 = dict(df_cibtow.query('bage == 2011').groupby(level=('city'))['pop'].sum())
    ## calculation of population share per building segment
    df_growth_new_bs['weight'] = (df_growth_new_bs['pop2011']
                  / df_growth_new_bs.index.get_level_values('city').map(lambda
                      x:dict_pop2011[x])
                  )
    # ALLOCATE WEIGHTED POPGROWTH to building segment
    df_growth_new_bs['pop growth'] = (df_growth_new_bs['weight']
                            * df_growth_new_bs.index.get_level_values(0)
                            .map(lambda x: dict_popgrow_ci[x]))
    # FILL
    ## fill btype and btype_owner because they are needed for df_ebs_grow
    for e,n in enumerate(df_growth_new_bs.index):
        df_growth_new_bs.loc[n,'btype'] = n[1] + '_' + str(n[2])
        df_growth_new_bs.loc[n,'btype_owner'] = n[1] + '_' + str(n[2]) + '_' + n[3]
```

```
    # create missing columns because they are needed for join with building stock dataframe
    df_growth_new_bs['energydemand'] = 0
    df_growth_new_bs['energysavings'] = 0
    df_growth_new_bs['floorarea'] = 0

    df_growth_new_bs['mobile population']      = 0
    df_growth_new_bs['immobile population']    = 0
    df_growth_new_bs['mobile population shrinkage'] = 0
    df_growth_new_bs['immobile population shrinkage'] = 0
    df_growth_new_bs['pop shrink']             = 0

    # add growth column to building stock dataframe
    df_cibtow['pop growth'] = 0

    df_growth_newbs = df_growth_new_bs[df_cibtow.columns]
    return df_growth_newbs
```

A.1.4 shri

```
def keycolumns(s):
    # generate key columns in building stock dataframe
    btype = s[1] + '_' + str(s[2])
    btype_owner = btype +'_' + s[3]
    return btype,btype_owner

def shrifac_def(btypes):
    # define the allocation of shrinkage across building segments
    shrifac_mob={} # shrinking factor for mobile part of the building segment population
    shrifac_imo={} # shrinking factor for immobile part of the building segment population
    for o in btypes:
        #osplit = o.split('_')
        bcat= o[0] #o[1:3]
        bage= o[1] #o[-2:]
        btype = bcat + '_' + str(bage)
        MFHfactor = 1
        EFHfactor = 0
        # define the allocation of shrinkage across building segments
        if bcat == 'MH' and int(bage) > 49 and int(bage) <96:
            # Multi-family buildings are 100% mobile
            shrifac_mob[btype + '_rented'] = MFHfactor
            shrifac_imo[btype + '_rented'] = 1 - MFHfactor
        else:
            # Single-family and row houses are 0% mobile
            shrifac_mob[btype + '_rented'] = EFHfactor
            shrifac_imo[btype + '_rented'] = 1 - EFHfactor
        # all owner occupied buildings are not shrinking
        shrifac_mob[btype + '_owneroccupied'] = 0
        shrifac_imo[btype + '_owneroccupied'] = 0
    return (shrifac_mob, shrifac_imo)

def func(df_bstock_cibtow, dict_popshri_ci, btypes, np, label):
    # introduce key columns in building stock dataframe
    arr_keys = np.array([keycolumns(z) for z in df_bstock_cibtow.index])
    df_bstock_cibtow['btype'] = arr_keys[:,0]
```

```
df_bstock_cibtow['btype_owner'] = arr_keys[:,1]

# define the allocation of shrinkage across building segments
arr_shrifacs = shrifac_def(btypes)
shrifac_mob = arr_shrifacs[0]
shrifac_imo = arr_shrifacs[1]

# calculate mobile and immobile population with shrinkage factors
df_bstock_cibtow['mobile population'] =
   df_bstock_cibtow['btype_owner'].map(shrifac_mob)*df_bstock_cibtow['pop']
df_bstock_cibtow['immobile population'] =
   df_bstock_cibtow['btype_owner'].map(shrifac_imo)*df_bstock_cibtow['pop']

# determine shrinking factors for mobile and immobile population for each city to be used
    in each bseg
df_ebs_ci = df_bstock_cibtow.groupby(level=['city'])['pop','floor area','GEB',
                                     'immobile population','mobile population',
                                     ].sum()
df_ebs_ci['pop shrinkage' + label ] = df_ebs_ci.index.map(lambda x:dict_popshri_ci[x])
df_ebs_ci['pop shri diff' + label] = df_ebs_ci['pop shrinkage' + label] +
    df_ebs_ci['mobile population']
df_ebs_ci['pop shri fact mob' + label]= (df_ebs_ci['pop shrinkage' + label]
                            / df_ebs_ci['mobile population']).clip(lower=-1)
df_ebs_ci['pop shri fact imo' + label]= (df_ebs_ci['pop shri diff' + label]
                             / df_ebs_ci['immobile population']).clip(upper=0)
dict_popshrimobfac_ci=dict(df_ebs_ci['pop shri fact mob' + label])
dict_popshriimofac_ci=dict(df_ebs_ci['pop shri fact imo' + label])

# apply city specific shrinking factors for mobile and immobile population to each bseg
df_bstock_cibtow['mobile population shrinkage' + label] =
    (df_bstock_cibtow.index.get_level_values(0)
                                .map(lambda x:dict_popshrimobfac_ci[x])
                                * df_bstock_cibtow['mobile population']
                                )
df_bstock_cibtow['immobile population shrinkage' + label] =
    (df_bstock_cibtow.index.get_level_values(0)
                                .map(lambda x:dict_popshriimofac_ci[x])
                                * df_bstock_cibtow['immobile population']
                                )
# summing population shrinkage
df_bstock_cibtow['popShrink' + label] = ( df_bstock_cibtow['mobile population shrinkage' +
    label]
                                + df_bstock_cibtow['immobile population shrinkage' + label]
                               )
```